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INTEGRATED INTERNATIONAL SAFEGUARDS CONCEPTS FOR FUEL REPROCESSING

Los Alamos

LOS ALAMOS NATIONAL LABORATORY
LOS ALAMOS, NEW MEXICO 87545
US Department of Energy
Contract No. W-7405-ENG-36

Sandia National Laboratories

SANDIA NATIONAL LABORATORIES
ALBUQUERQUE, NEW MEXICO 87185
US Department of Energy
Contract No. DE-AC04-76DP00789

LA--8955

DE82 008974

LA-8955
SAND81-1311

UC-15
Issued: December 1981

Integrated International Safeguards Concepts For Fuel Reprocessing

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EXECUTIVE SUMMARY

This report is the fourth in a series of efforts by the Los Alamos National Laboratory and Sandia National Laboratories, Albuquerque, to identify problems and propose solutions for international safeguarding of light-water reactor spent-fuel reprocessing plants. Problem areas for international safeguards were identified in a previous Problem Statement (LA-7551-MS/SAND79-0108). Accounting concepts that could be verified internationally were presented in a subsequent study (LA-8042). Concepts for containment/surveillance were presented, conceptual designs were developed, and the effectiveness of these designs was evaluated in a companion study (SAND80-0160).

The report discusses the coordination of nuclear materials accounting and containment/surveillance concepts in an effort to define an effective integrated safeguards system. The Allied-General Nuclear Services fuels reprocessing plant at Barnwell, South Carolina, was used as the reference facility.

INTERNATIONAL SAFEGUARDS REQUIREMENTS

The effectiveness of International Atomic Energy Agency (IAEA) safeguards is measured by the ability to detect diversion of nuclear material by verifying the findings of the State's System of Accounting and Control of nuclear material. The inspector's verification procedure is based on periodic examination of the materials balance equation for each materials balance area (MBA). The inspector must determine that

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

These verification activities include (1) examination of safeguards-related information provided by the State, (2) collection of independent information by the IAEA, and (3) comparison of the two sets of information to establish the completeness, accuracy, and validity of the State's data. The IAEA uses methods drawn from materials accounting and containment/surveillance, augmented by an appropriate level of inspector presence, to implement its verification responsibilities.

SAFEGUARDS CONCERNS

The IAEA verification of the operator's nuclear materials accounting information is based on examination of the materials balance equation with respect to

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

Diversions hidden by measurement uncertainties are possible because of the statistical errors always present in the measurements used to form the materials balance. It is important that measurement uncertainties be reduced to decrease the amount that could be diverted, but also that the estimate of measurement uncertainties be realistic to maintain false-alarm rates at an acceptable level.

Concerns with diversion hidden by falsification of operator's data, that is, falsification of suitable terms in the materials balance equation, fall into three categories:

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

In the reprocessing facility, falsifications may be correlated among MBAs. For example, an overstatement of outputs from one MBA will result in an overstatement of inputs to the next MBA. Detection of diversion in one MBA is related to the adequacy of safeguards in adjacent MBAs, and correlation of verification activities and results among MBAs is important.

VERIFICATION ACTIVITIES

We assume that the operator's accounting system for the reference facility is a combination of conventional materials accounting and near-real-time accounting. Conventional materials accounting depends on periodic shutdown, cleanout, and physical inventories. For near-real-time accounting, the in-process inventories of major process vessels and columns are measured or estimated, without interrupting process operations, to permit frequent closure of materials balances. Although it may be impractical to make sufficiently sensitive measurements of inventory at an adequate frequency to achieve timely detection, it is possible to use surveillance of containment boundary penetrations in conjunction with normal transfer measurements to achieve timely detection in a particular MBA.

The inspector compares the operator's and his own materials accounting data and examines information from the containment/surveillance system to ensure that diversion has not occurred. The inspector must establish an independent verification capability for each key measurement point (KMP). If an inspector wishes to use data from certain KMPs and knows that they are unfalsified, he must ensure measurement integrity by participation in measurement control programs and surveillance of measurement procedures, and he must assure integrity of the instruments with inspector-controlled surveillance devices. We have assumed that the reference facility will accommodate continuous inspector presence and that the inspector will have on-site laboratory facilities.

Three MBAs of the reference facility were considered: MBA 1, the fuel receiving, storage-chop/leach; MBA 2, the chemical separations process; and MBA 4, the plutonium-nitrate storage area. The input, output, and inventory KMPs for these MBAs were identified. The uranyl-nitrate storage area (MBA 3) was not treated. Emphasis in this study was on safeguards verification for plutonium. It was assumed that verification of conventional safeguards measures for uranium would satisfy IAEA requirements.

Verification in MBA 1

For transfer and inventory measurements in the fuel receiving and storage area of MBA 1, the inspector will check the identity of the spent-fuel assemblies by reading the serial numbers or by interrogating fuel assembly identification devices. He may also perform rapid qualitative measurements of assemblies or verify quantitative measurements of a limited number of fuel assemblies.

Surveillance of KMPs in MBA 1 includes spent-fuel monitors at the cask-unloading pool and before the entrance of the spent-fuel transfer tunnel, and optical surveillance in the spent fuel storage area. Penetrations in the containment boundaries of the spent-fuel storage area and the chop/leach area are monitored to prevent bypass of KMPs and to provide timely detection of undeclared inventory changes.

Verification in MBA 2

The inspector's verification activities in MBA 2 are concerned with accurate volume, density, and concentration measurements to verify flow through KMPs and inventories in KMPs.

The transfer KMPs are monitored by surveillance instruments to prevent bypass or other manipulation of transfers. A simple data processing system is required to correlate the data from various sensors at a KMP so that the proper sequence of operations can be monitored.

Verification in MBA 4

For MBA 4, the plutonium-nitrate storage area, verification of volume, density, and concentration measurements is required at the flow and inventory KMPs. Penetrations in the containment boundary of MBA 4 are monitored to ensure that the KMPs are not bypassed and to detect unreported inventory changes.

EFFECTIVENESS OF VERIFICATION ACTIVITIES

The inspector must use his resources efficiently and effectively to verify safeguards information. The effectiveness of the nuclear materials accounting system is established using statistically designed data evaluation techniques. Effectiveness of surveillance of containment boundary penetrations is determined by network analysis. These procedures also assist the inspector in planning inspection strategies.

Effectiveness of Materials Accounting

The inspector's problem of detecting operator's falsified data and diversion hidden by measurement uncertainties is treated in this report by applying inspector's sufficient statistics that protect against both diversion and data falsification. The performance of these statistics in detecting abnormalities was evaluated for a range of diverted amounts in the chop/leach area of MBA 1, in MBA 2, and in MBA 4. In each case the analysis assumes valid inspector's data and the optimal operator's data falsification strategy. Also, all of the sensitivities presented assume that the inspector either has a measurement method with uncertainty comparable to the operator's method or can verify the operator's measurement and use it as his own. In all other cases, the inspector's detection probability is lower.

The separations process (MBA 2) of the reference facility is the most likely area for application of these methods because quantities of material are relatively small and measurement techniques for this area are well developed. If the inspector uses the inspector's data only in testing for missing material without regard to operator falsification, the inspector's sufficient statistic has the sensitivity to missing material to meet the IAEA goal for detecting abrupt diversion, assuming that the inspector's and operator's measurement uncertainties are equal. For 8 kg of plutonium diverted in 7 days, the inspector has a detection probability of 0.97. If the inspector uses the operator's unverified measurements, then he must test for data falsification and/or diversion and accept a slightly reduced sensitivity. For this test, the detection probability is 0.94.

Although the chop/leach area and MBA 4 have not traditionally been considered in near-real-time accounting, evaluation of the inspector's sufficient statistics in these areas shows that substantial probabilities of detecting missing material can be attained. In the chop/leach area, 8 kg of plutonium diverted in 7 days is detected with probability 0.64 if the inspector tests only for diversion hidden in measurement uncertainties and with 0.56 probability by testing for diversion and/or falsification. For MBA 4 the respective probabilities are 0.26 and 0.21.

These probabilities of detecting diversion and/or falsification in MBA 4 could be increased to meet the IAEA goal for detecting abrupt diversion by (1) reducing the number of slab tanks in the MBA and (2) reducing the amount of plutonium in each tank. If we assume storage capacity of 60 days of throughput is required for a plant with a collocated conversion facility, 30 slab tanks, each with 100 kg of plutonium, would be required for MBA 4. If we assume storage capacity for 20 days of throughput is sufficient, 10 slab tanks, each with 100 kg of plutonium, would be adequate for MBA 4.

Sensitivities of the inspector's sufficient statistics for detecting diversion hidden by measurement uncertainties, independently of data falsification, are shown in Table S-I.

TABLE S-I

SENSITIVITY OF INSPECTOR'S SUFFICIENT STATISTIC FALSIFICATION INDEPENDENT

	Detection Probability[a]			
	Balance Period (days)			
	7	30	180	360
Chop/leach	0.64	0.25	0.11	0.09
MBA 2	0.97	0.82	0.25	0.20
MBA 4; 9.9 MT	0.26	0.24	0.17	0.13
MBA 4; 3 MT	0.81	0.73	0.24	0.13
MBA 4; 1 MT	0.99	0.90	0.26	0.15

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

Effectiveness of Containment/Surveillance

Surveillance of containment boundary penetrations was considered in this report as a safeguards measure to provide additional safeguards assurance for areas of a reprocessing plant where irreducible measurement uncertainties or operational constraints preclude timely or accurate materials balance accounting. Accordingly, conceptual containment/surveillance systems of this type were designed for MBAs 1 and 4. A useful measure of the safeguards assurance is the probability of at least one alarm during diversion of a specific amount over a given time period, with a specified false-alarm rate. Using data from sensor modeling for six generic sensor types, systems sensitivity and false-alarm rates were computed for time periods ranging from 10 days to 360 days. In each case, a range of diversion amounts was considered. The results are summarized in Table S-II.

The results suggest that for MBAs 1 and 4 abrupt diversion of a significant quantity has a probability >0.95 of generating at least one surveillance alarm. In MBA 1, even protracted diversion of a significant quantity has a similar risk of generating an alarm.

Another role for containment/surveillance is the verification of measurement information for the inspector. Preliminary analyses of potential falsification scenarios suggest that fairly extensive surveillance systems may be required. However, there is no generally accepted methodology for designing or evaluating surveillance systems to verify measurements, and thus it is impossible to estimate the effectiveness of such systems.

TABLE S-II

SENSITIVITY OF PENETRATION-MONITORING SYSTEMS

	Detection Probability[a]			
	Balance Period (days)			
	10	30	180	360
MBA 1	>0.95	>0.95	>0.95	>0.95
MBA 4[b]	>0.95	0.82	0.26	0.19

[a]Probability of at least one alarm during the diversion of 8 kg of plutonium with an expected false-alarm rate of 0.019 per day in MBA 1 and 0.010 per day in MBA 4.

[b]Computed for MBA 4 configured to store 9.9 MT of plutonium.

Quantifying the Assurance for Materials Accounting and Containment/Surveillance

The overall assurance is a combination of the assurance

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

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

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

The factors contributing to this equation are difficult to quantify; hence, at present it can only provide a qualitative indication of the relationship among the component assurances. The equation shows that a high level of assurance solely from materials accounting or boundary penetration surveillance is not sufficient.

RECOMMENDATIONS

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

Verification Approach

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

- appropriate statistical test procedures for materials accounting data from each MBA to detect diversion of a significant quantity of nuclear material,

- surveillance of the containment boundary penetrations for MBA 1 and MBA 4,
- surveillance of KMP measurement devices and procedures for all MBAs,
- inspector participation in the measurement control program for materials accounting and surveillance instruments, and
- an on-site inspector's analytical laboratory with appropriate analytical instruments and standards.

Facility Design to Improve Verification Effectiveness

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

Considerations in facility design and operation affect the application of conventional and near-real-time accounting techniques to reprocessing facilities. Process design and operational considerations that affect measurement quality include

- relative accuracy between input and output measurements (the limiting factor will be the uncertainties in the fundamental constants; that is, the relative biases between reference materials and methods used for measurements);
- precision and relative accuracy of cleanout physical inventory measurements;
- redundant methods at KMPs to reduce systematic errors; and
- for near-real-time accounting, the precision of in-process inventory estimates and measurements.

Important considerations of containment include

- the number of penetrations through MBA containments,
- identifying and verifying required penetrations,
- providing multiple containment boundaries where feasible,
- a penetration design to minimize surveillance requirements,
- the use of containment to provide a barrier between personnel and nuclear material, and
- coordination of containment boundary design and maintenance philosophy.

Considerations of importance for surveillance are

- surveillance device sensitivity and an acceptable false-alarm rate,
- surveillance device reliability and, where necessary, redundancy and variety to aid in resolving anomalies,
- surveillance device provision in facility design, and
- tamper protection for surveillance devices.

Considerations of importance to the inspector include

- assurance that all significant nuclear materials flows and inventories are accessible for verification at KMPs and
- assurance that the inspector is provided a sufficient set of unfalsified data.

CONCLUSIONS

In this study a safeguards strategy was developed that includes materials accounting and containment/surveillance tradeoffs without requiring explicit assurance functions or combined systems evaluations. The study indicates that the implementation of near-real-time accounting in the reference facility would not require significantly more measurements than are required for the process control and conventional materials accounting measurements that were originally planned for the facility. Appropriate statistical test procedures can combine accounting information that has been verified by the inspector with potentially falsified operator's accounting information to provide a significant level of safeguards assurance. In particular, these techniques should allow the inspector to satisfy the IAEA guidelines for detecting abrupt diversion in MBA 2. The amount of plutonium in MBA 4 limits safeguards effectiveness of materials accounting in this MBA. *We recommend that plutonium storage be limited to the amount required for* reprocessing and conversion operations so that IAEA guidelines for detecting abrupt diversion can be met. Achievement of the IAEA guidelines for timely detection of protracted diversion from MBAs 2 and 4 remains a safeguards problem caused by irreducible measurement uncertainties and high plant throughput.

The safeguards assurance derived from the materials accounting system depends on the effectiveness of the inspector's verification activities. Surveillance measures that may aid the inspector in verifying measurement information are identified. It seems likely that extensive surveillance systems will be necessary to provide the required level of verification. However, no systematic method for designing or evaluating surveillance of measurement points exists. A continuing effort will be necessary to develop these techniques and demonstrate that measurements at KMPs can be verified.

Penetration-monitoring systems potentially can provide a high level of safeguards assurance that abrupt diversion from MBA 4 and abrupt or protracted diversion from MBA 1 would trip a surveillance alarm. In practice, achieving this assurance will depend upon the successful development of surveillance devices that have performance characteristics similar to those attributed to the generic devices considered in this report.

Selected components for an inspector-verifiable near-real-time materials accounting system and for a containment/surveillance system have been installed and are being evaluated as a continuing safeguards demonstration program at the AGNS Barnwell facility. Continuation of this program is necessary for international acceptance of the systems.

A single figure of merit for the aggregate safeguards system was not developed in this study. No known method exists for properly quantifying the interdependencies of the various safeguards techniques. The stated performance of materials accounting and containment/surveillance is, of course, dependent upon an adequate assurance of valid inspector data, and that assurance is not yet quantifiable. Thus, this report has emphasized the functional definition of appropriate safeguards system elements for a large-scale reprocessing plant.

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GLOSSARY

AGNS	Allied-General Nuclear Services
BNFP	Barnwell Nuclear Fuels Plant
BWR	boiling water reactor
DOE-OSS	Department of Energy-Office of Safeguards and Security
DPS	data processing system
FAID	fuel assembly identification device
HAW	high-activity waste
HLC	high-level cell
HRGS	high-resolution gamma-ray spectrometry
HWW	high-level liquid waste
IAEA	International Atomic Energy Agency
IDMS	isotope-dilution mass spectrometry
ISS	inspector's sufficient statistic
IWG-RPS	International Working Group-Reprocessing Plant Safeguards
KMP	key measurement point
LWR	light-water reactor
MBA	materials balance area
MUF	materials unaccounted for
MWd/MTHM	megawatt days per metric tonne of heavy metal
NBL	New Brunswick Laboratory
NBS	National Bureau of Standards
NDA	nondestructive assay
pdf	probability density function
PWR	pressurized water reactor
RSD	relative standard deviation
SD	standard deviation
SNLA	Sandia National Laboratories, Albuquerque
SQ	a significant quantity of material
S/R	shipper/receiver
SSAC	State's System of Accounting and Control
T	detection time
TBP	tributyl phosphate
TLD	thermoluminescent detectors
UPAA	unit process accounting area
US	United States
XRF	x-ray fluorescence

PUREX PROCESS IDENTIFIERS

Contactors

A	extraction-scrub for U-Pu or Pu alone
B	U-Pu partition or Pu strip
C	U-Pu strip
D	extraction-scrub for Pu alone
H	preparation columns or streams

Stream

A	aqueous
F	feed
IS	intermediate scrub
O	organic
P	product containing Pu or Pu + U
R	raffinate (no appreciable U or Pu)
S	scrub
U	product containing only U
W	waste (no appreciable U or Pu)
X	extractant

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by

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ABSTRACT

The integration of materials accounting and containment/surveillance for a nuclear fuel reprocessing facility under international inspection was considered. The study evaluates the safeguards concerns and International Atomic Energy Agency (IAEA) verification activities for the fuel-storage and chop/leach, chemical separations, and plutonium-nitrate storage materials balance areas (MBAs) using the Allied-General Nuclear Services plant as a reference facility. If the inspector verifies sufficient near-real-time accounting measurements, he can meet IAEA goals for detecting abrupt diversion in the chemical separations MBA. Using near-real-time accounting, substantial probabilities for detecting diversion in the chop/leach portion of the headend and in the product storage MBA can be attained, but IAEA abrupt diversion goals cannot be met rigorously. IAEA goals for detecting protracted diversion cannot be met in any of the MBAs.

Penetration-monitoring concepts in the headend and product storage MBAs were developed. This methodology is based on the probability of generating an alarm during a diversion occurring over a specified time. The evaluation suggests that for abrupt diversion a high level of safeguards assurance potentially can be attained in both MBAs. In addition, there is a high probability that protracted diversion from the fuel-storage and chop/leach MBA will generate a surveillance alarm. Protracted diversion from the plutonium-nitrate storage MBA remains a significant safeguards problem.

Although a functional relationship among the assurances for elements of materials accounting and containment/surveillance was developed in this study, quantifying that assurance is not possible at this time.

I. INTRODUCTION

The introduction of reprocessing facilities into the commercial nuclear fuel cycle has underscored concern that material produced in such a facility might be diverted from the fuel cycle, possibly for production of nuclear explosives. It is in the reprocessing facilities that plutonium is first obtained in a form free of fission products and uranium, and thus, it becomes more attractive for weapons manufacture.

This concern over nuclear weapons proliferation has spurred the United States (US) and other nations having advanced nuclear programs to assess potential improvements in safeguards technology. Through the US Department of Energy, Office of Safeguards and Security (DOE-OSS), the Los Alamos National Laboratory and Sandia National Laboratories, Albuquerque, New Mexico, (SNLA) were tasked to study improved international safeguards methods for large reprocessing facilities of the type that may be under International Atomic Energy Agency (IAEA) safeguards in the last decade of this century. This report describes international safeguards methods that will assist the IAEA in the verification of nuclear materials accounting information provided by the operator's or State's accounting system.

Effective international safeguards systems must be based on an intelligent integration of improved materials accounting, containment/surveillance, and inspection activities. This report presents concepts based on a combination of independent measurements by on-site inspectors and surveillance, either by inspectors or instruments, applied at selected measurement points and at containment boundary penetrations to verify the operator's materials accounting results. No technique should be treated as an independent system, but as a complementary element in an overall approach. At the same time, the integrated system must satisfy the practical constraints of cost, intrusiveness into process operations, available (or reasonably projected) technology, and resources.

A. Previous Los Alamos and SNLA Work

The overview of the problem and the technological approach to be taken were outlined in Ref. 1. The previous Los Alamos study on materials accounting concepts for future high-throughput nuclear fuel reprocessing facilities considered using conventional item or bulk accounting in the headend (fuel receiving and storage-chop/leach) and plutonium-nitrate product storage materials balance areas (MBAs), and overlaying near-real-time accounting with conventional materials accounting for the reprocessing

MBA.[2,3] The near-real-time accounting strategies treated the whole MBA as a single unit process accounting area (UPAA) with materials balance closures every 2 days or alternatively divided the MBA into two UPAAs with materials balance closures every 9.6 h.

The SNLA study[4] described methods for selection of containment boundaries and identification of containment boundary penetrations and measures for monitoring containment boundaries. A conceptual design of a containment/surveillance system for a Barnwell-type reprocessing plant was developed.

In addition, both Los Alamos and SNLA have participated in the IAEA-sponsored International Working Group on Reprocessing Plant Safeguards (IWG-RPS). This group of experts provided a forum for considering aspects of current and proposed safeguards techniques, and the authors have drawn on the IWG-RPS work in this report.

B. Reference Facility Description

The existing Allied-General Nuclear Services (AGNS) Barnwell Nuclear Fuel Plant (BNFP)[5-7] was selected as the reference reprocessing facility for the previous SNLA and Los Alamos studies and was used again in this study. The AGNS plant is designed to receive and process irradiated power-reactor fuel that originally contained UO_2, or UO_2 and PuO_2, at 3.5% ^{235}U enrichment or 29 kg of fissile plutonium per tonne before irradiation. Fuel batches having an average burnup not exceeding 40 000 MWd/MTHM (megawatt days per metric tonne of heavy metal) are processed at rates up to 5 MTHM/day after a minimum decay period of 160 days.

The BNFP uses the Purex recovery process that has been in large-scale use for ∿25 yr and is used, with minor variations, by most of the reprocessing plants now operating or planned throughout the world.

The facility is designed to use conventional Purex technology to process 1500 MTHM/yr of nuclear fuel and to recover 15 MT/yr of plutonium as the nitrate solution. The BNFP was selected as a typical plant that will be required in the future to support a mature nuclear industry. Process flows through the reference plant and basic process functions and chemistry are reviewed in Ref. 6 and in Appendix B of Ref. 3. Each major plant area is described briefly in the following sections.

1. Spent-Fuel Receiving and Storage. The spent-fuel assemblies arrive at the reprocessing facility by rail or truck and are held in a fuel-storage pool to await processing. All operations that involve handling bare spent-fuel assemblies, from cask-unloading to the transfer of assemblies into the chemical separations area, are performed underwater in a series of pools, using various overhead bridge cranes. Fuel

assemblies are removed from the casks and stored underwater in baskets until they are required for processing. At that time, assemblies are removed one at a time from the baskets and transferred individually by underwater conveyor to the adjacent remote process cell.

2. Chop/Leach. In the remote process cell spent fuel is mechanically sheared and dissolved with concentrated nitric acid. The remote process cell and remote maintenance and scrap cell are mechanically maintained by a crane and remote manipulation; under normal conditions there is no provision for personnel access once operation begins. Shielding doors and hatches are provided between the cells and a crane equipment and maintenance gallery. When the doors are closed, the gallery may be entered by personnel for maintenance of the crane and other equipment.

3. Chemical Separations. The dissolver solution is contacted with tributyl phosphate (TBP) in a normal paraffin hydrocarbon solvent (dodecane) to separate most of the fission products from the plutonium and uranium. The solvent stream containing plutonium and uranium enters the partitioning step where the bulk of the uranium is separated from the plutonium. The uranium stream is further decontaminated with a solvent-extraction, aqueous-strip cycle and is then concentrated. The concentrated uranyl nitrate passes through silica-gel beds to remove traces of zirconium and niobium and is stored in the uranyl-nitrate storage area. The plutonium stream from the partitioning cycle is further purified in two separate solvent-extraction and acid-strip process steps. The plutonium-nitrate solution is concentrated and transferred to the nitrate storage area. Solvents used in the purification process are treated to remove fission products and degraded organics and are recycled to the plant. Wastes from the processes are treated in either liquid- or solid-waste processing systems, and off-gases are treated before being vented to the atmosphere.

The operations discussed above are performed in five remotely operated, contact maintenance process cells: the high-level, high-intermediate-level, intermediate-level, plutonium product, and uranium product cells. Thick concrete walls, ceilings, and floors provide biological shielding from various highly active process solutions. The uranium product cell and plutonium product cell have exterior gloveboxes for sampling purposes.

A sample and analytical cell is provided for sampling other process solutions; normal operations are performed using remote manipulators. Samples from this cell as well as from the gloveboxes are bottled and transferred pneumatically to the analytical laboratory for analysis.

4. Plutonium-Nitrate Storage. The plutonium-nitrate storage area provides interim storage of plutonium nitrate between the separations area and a colocated conversion facility. The solution is stored in slab tanks until needed by the conversion process. These storage tanks are located within two plutonium-nitrate storage cells that are shielded by their heavy concrete construction. Solution is pumped between tanks, to sampling tanks, back to the chemical separations area for recycle, and to the conversion facility. Valves, piping, and pumps for the sampling and transfer operations are housed within gloveboxes. Samples are bottled in gloveboxes and then sent to the analytical laboratory through pneumatic transfer tubes.

C. Organization of the Report

This study presents concepts for international safeguards in which an integrated materials accountability and containment/surveillance system provides verification of the State's materials accounting reports. The integrated system uses technology and hardware that are currently available or can be reasonably projected to be available at the time of future facility design and construction.

Section I reviews the basis for this study and briefly describes the reference facility. Safeguards concerns for international verification and an approach to verification activities are discussed in Sec. II. Section III reviews basic design approaches for materials accounting and containment/surveillance, and for integration of these elements. Detailed concepts of integrated safeguards and verification activities for the reference facility are described in Sec. IV. Section V suggests inspector evaluation methodology and presents results of the application of this methodology to advanced materials accounting and containment/surveillance systems. Section VI reviews the results and conclusions of the study and makes recommendations to improve the effectiveness of IAEA verification activities in future high-throughput reprocessing facilities.

Appendix A reviews measurement methods that are proposed for operators' and inspectors' activities. Appendices B and C present the derivation of the mathematical approach to inspector verification of materials accounting and containment/surveillance information, respectively.

II. VERIFICATION APPROACH

A. The Basis for IAEA Safeguards

The chief goal of the international nonproliferation effort is to prevent the spread of nuclear weapons, while promoting peaceful uses of nuclear energy, as described in various documents such as the Nonproliferation Treaty,[8] Information Circular (INFCIRC)/153,[9] and INFCIRC 66.[10] IAEA safeguards are basic in pursuing these nonproliferation goals.

The safeguards environment provided by the IAEA has two primary aspects: deterrence and assurance. A nation contemplating diversion of nuclear material might be reluctant to subject itself to the possible consequences for its action. Thus, safeguards "deter diversion by risk of early detection."

The most common result of IAEA safeguards activities should be a finding of no diversion because nations enter safeguards agreements voluntarily and may be expected to abide by them. The world community relies on the IAEA to provide assurance that its members have not violated these agreements, and the degree of assurance derives from the perception that violators will be exposed. In addition, this monitoring capability provides the basis for increased mutual confidence among nations concerned with nonproliferation.

The effectiveness of IAEA safeguards is closely related to its capability to detect diversion of nuclear material. However, in some measure, the effectiveness is a subjective quantity dependent on the perceptions of both divertors and those wishing to be assured that no diversion has occurred. The divertor's assessment that he is likely to be caught, and the nondivertor's assessment that a finding of no diversion is valid because diversion probably would have been detected, are important factors in IAEA safeguards.

Detection capability is effected by the IAEA's verification of the State's System of Accounting and Control (SSAC) as specified in paragraph 7 of Ref. 9. (Verification here is meant in the broad sense of checking the validity of the information from the SSAC.) As outlined in the Safeguards Technical Manual,[11] the Agency's verification activities apply to the location, identity, quantity, and composition of all nuclear material subject to safeguards. The verification process generally consists of three steps: (1) examination of safeguards-related information provided by the State, (2) collection of independent information by the IAEA, and (3) comparison of the two sets of information to establish the completeness, accuracy, and validity of the State's date. In fulfilling its responsibilities the IAEA uses methods drawn from materials accounting and containment/surveillance techniques, both augmented by an appropriate level of inspector presence.

The SSAC must provide the Agency with information concerning nuclear material and facility features that are relevant to safeguarding such material. The information provided to the Agency comprises:

(1) design information relevant to safeguards, including important features of
    - (a) the facility layout,
    - (b) the process, and
    - (c) the accounting system;

(2) accounting reports for each MBA, including
    - (a) inventory change reports and
    - (b) materials balance reports; and

(3) special reports regarding
    - (a) losses of nuclear material or
    - (b) changes in the facility design.

Design information will be verified before the facility becomes operational, and portions of the information will be periodically reverified. The importance of design verification is not minimized for any safeguards technique although different approaches require different levels of design verification. The process of design verification has been discussed by the Design Considerations subgroup of the IWG/RPS[12] and will not be addressed further in this report.

This report deals primarily with the verification of information provided in compliance with (2) above. Verification of special reports regarding losses of nuclear material (3.a) may be performed in part through the same procedures used for normal accounting reports; however, special inspections may be required under some circumstances. Verifying special reports concerning changes in facility design, in most cases, would require procedures similar to those for verifying original plant design information.

Verification of materials accounting reports is based on a periodic examination of a materials balance equation for each MBA. In each MBA the material unaccounted for (MUF) is determined by the following equation:

$$\text{MUF} = \text{inputs} - \text{outputs} + \text{previous inventory} - \text{current inventory} .$$

This calculation is accompanied by a statement of the uncertainty in the MUF value. If MUF is sufficiently small compared to the uncertainty of the calculation, it can be concluded that no significant diversion has occurred, assuming that the materials accounting information is valid and complete. Otherwise, further investigation is warranted.

The primary calculation of MUF and its uncertainty is done under the aegis of the SSAC and presented to the Agency inspector for verification. The inspector's problem is twofold. First, he must determine whether the materials accounting data reported to him are valid and complete, and second, he must determine whether the materials balance equation closes sufficiently near zero. The inspector may perform these verification activities in many ways, depending on such factors as effectiveness, efficiency, and cost. Detailed consideration of options available to the inspector requires further examination of safeguards concerns relevant to his verification capability. These concerns are the topic of the next section.

B. Safeguards Concerns

In this report we consider the problem of a divertor whose ultimate goal is to divert a quantity of nuclear material while minimizing the possibility that the Agency will detect the diversion in a timely manner. Because of the IAEA's method of verification, which is based on an examination of a materials balance equation, a divertor must induce the inspector to conclude that the materials balance equation provides no evidence that diversion has occurred. Such concealment methods may be grouped in two classes :

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

The first method is possible because of the statistical uncertainty in the MUF calculation. If the uncertainty is relatively large, a relatively large amount of material could be diverted without causing the value of MUF to be abnormally large compared to its uncertainty. This method of concealment may be a particular concern in areas where measurements are difficult to make.

Another method of concealment is for the facility operator to reduce the apparent MUF by falsifying suitable terms in the materials balance equation. Examination of that equation shows that a reduction in the apparent MUF can be accomplished by :

- understating declared inputs,
- overstating declared outputs, or
- overstating the current declared inventory.

We first examine the implications of these types of falsification and then consider methods of generating such misstatements.

1. Falsification Possibilities. Understating inputs involves accumulating nuclear material in the MBA that does not appear on the accounting records and thus can be diverted without detection by the materials accounting system. In effect, nuclear material can enter the MBA without a proper input measurement. This nuclear material may be obtained from an adjacent MBA or from another facility that is outside safeguards (undeclared feed). It is likely that the only undeclared feed of concern at a reprocessing plant under international safeguards is spent fuel. We therefore assume that, except for spent fuel, the only methods of input understatement involve nuclear material leaving one MBA to enter another.

If an input for one MBA is understated, the MUF for the corresponding upstream MBA will tend to show a positive value because the understated input also appears as an understated output from the upstream MBA. Therefore, except for the possibility of introducing spent fuel as undeclared feed, attempted concealment may be detected in the upstream MBA. However, detecting diversion of material from the upstream MBA will then depend upon the adequacy of safeguards in that MBA. Thus, the correlation of verification activities among MBAs is important.

The method of output overstatement can be used to remove nuclear material from accounting records by reporting it as having been transferred out of the MBA through legitimate output streams. In the same manner that understatement of inputs depends on where the material originates, overstatement of outputs depends upon where material goes. In this case, attempted concealment may be detected in the downstream MBA; however, detection of diversion of material from the MBA of interest will then depend upon the adequacy of safeguards in the downstream MBA.

The tampering procedures used to cause overstatement can be very different from those used to cause understatement. For example, understatement may be obtained by omitting measurements, whereas overstatement may be accomplished by multiple measurements of the same material. On the other hand, both understatement and overstatement may be obtained through measurement bias, but of opposite signs in the two cases.

If an output stream contains material such as waste that is leaving safeguards, then the divertor has no MBA correlation problem. However, we assume that there will be limits placed on the amount of material that is reported to have left by way of such streams. If these limits are sufficiently low that even repeated overstatement of waste outputs would not allow concealment of a significant diversion, overstatement of these outputs is of less concern.

Overstating the current inventory is similar to understating inputs, in that it creates a reservoir of nuclear material in the MBA that can be diverted without immediate detection by the materials accounting system. However, for any particular inventory measurement point, the amount of overstatement is limited by the maximum capacity at that measurement point. If the diversion is a one-time removal, the overstatement must be repeated at each subsequent inventory measurement. If the diversion is protracted, the overstatement must be increased with each successive removal and repeated at the final value once the diversion is finished.

The amount of overstatement for the MBA is limited by the amount of the maximum total process inventory for the MBA. It would be impractical, however, to remove the entire process inventory and still operate the process. Thus, the total overstatement that is possible without process shutdown will be limited by the difference between maximum and minimum process inventories during operation.

2. Falsification Mechanisms. The falsification procedures just discussed depend on details of the specific measurements and inspector awareness of all aspects of the measurement processes. A categorization of general falsification mechanisms comprises the following types:[2]

- materials tampering,
- instrument tampering,
- data tampering, and
- statistics tampering.

We consider each of these briefly, reserving detailed consideration of specific falsification activities for Sec. IV.

Materials tampering (that is, when the operator's instruments measure suitably constituted material other than that declared) can occur when the process is operated in such a way that material is not measured or is measured more than once. To achieve understatement, the operator could simply fail to measure the material in an input stream by either bypassing the measurement point or by making no measurement when the materials passed through that point. In addition, the operator could remove some of the material from the measurement point during the measurement by, for example, circulating the material through the sampling loop while making a volume measurement.

To achieve overstatement, the operator would make it appear that there is more material at the measurement point than there actually is. For example, he could inflate the volume measurement by running an air sparge at the time of the measurement, or temporarily place material in the measurement point from some other place. For output measurements, the same material might be measured more than once before being transferred. For either overstatement or understatement, the operator could tamper with the material being sampled by failing to homogenize the solution before sampling or by substituting sample solution from some other place.

Instrument tampering requires some means of causing the instrument to produce an incorrect measurement. These means include rendering the instrument inoperative to cause understatement and inducing bias to conceal either overstatement or understatement.

The objective of data tampering is to report suitable false measurement results to the inspector; it can occur any time from the output of the instruments until the data are reported to the inspector.

Tampering with measurement-error statistics would allow the divertor to conceal a higher level of diversion within the measurement uncertainties. For example, the divertor could try to convince the Agency that the statistical errors associated with a set of instruments are larger than they truly are. The divertor might subvert the measurement-control program to achieve this objective. The result would lower the probability of detection, with a corresponding decrease in the false-alarm rate.

C. Verification Activities

We have considered safeguards concerns in the light of the Agency's verification responsibilities. In this section we focus on verification activities, although specific procedures are discussed later.

As we have stated, the verification process has three steps:[11] (1) examining the information provided by the State in the design information questionnaire, the initial accounting reports, and subsequent routine and special accounting reports; (2) collectng information by the IAEA at inspections; and (3) evaluation of the information provided by the State and collected by the IAEA to establish the completeness, accuracy, and validity of the State's information. The resolution of anomalies, sometimes called assessment or response to alarms, is an important topic that we have chosen to address separately, though it may be part of the evaluation step.

1. Examination of State's Evidence. The State will provide data concerning inventory changes and materials balances for each MBA. When the information is received, it will be examined for completeness and consistency. Concealment of diversion may require reporting falsified data at several times and for several measurement points. If these falsifications are not correlated, examining the data for consistency may reveal the falsifications.

The data may also be examined to determine if they are consistent with normally expected operating conditions. As mentioned earlier, process holdup may be expected to vary within known limits. Furthermore, reported waste outputs should not exceed previously agreed upon limits.

2. Collection of Data for Verification Purposes. Data will be collected independently by the Agency for comparison with the data provided by the State. The independent information will include materials accounting and containment/surveillance data as well as other information provided by direct inspector observation. It is not intended that the State's reported values be duplicated, only that the minimum amount of data necessary for verification be collected.

During this step the Agency must decide (1) if the collected data are sufficient to verify the State's findings, and (2) if the collected data are truly independent. These questions must be answered in the context of the safeguards concerns discussed earlier.

Generally, inspector activities for verifying the operator's reported values can be roughly divided into two categories: (1) those intended to verify particular values reported by the operator, and (2) those intended to verify the operator's measurement procedures. The first category requires that the inspector make a set of materials measurements, perhaps on a sampling basis. The inspector's values and the operator's reported values are then combined to measure the veracity of the operator's values. The second general category of inspector activities comprises those procedures intended to ensure the fundamental honesty of the operator's measurement processes and the continued integrity of these measurement results. Those measurements that must be witnessed by the inspector because they cannot be duplicated also might be included. Often this kind of information can be provided by containment/surveillance devices applied to certain of the operator's measurements.

In many cases, a particular measurement can be verified only by a combination of these techniques because, for example, although the inspector may use his own instrumentation, he is dependent upon the operator's piping, sampling system, or measurement procedures.

The techniques available to inspectors include independent materials measurements, surveillance of measurement procedures and the status of instruments and data, surveillance of containment boundary penetrations[4] to detect flows of nuclear material outside of normal flow paths, and his own observations. Each of these can be used to address the falsification mechanisms described.

In general, the falsification mechanism of materials tampering is difficult to detect by independent measurements because it is the material presented for measurement that has been tampered with rather than the measurement itself. Surveillance devices can be used to monitor many measurement procedures, and, in some cases where the inspector can observe the material, observation of a measurement may be useful.

Appropriate containment boundaries and surveillance of containment boundary penetrations can be used to provide assurance that material does not bypass input measurement points or is measured repeatedly at output or inventory measurement points. The inspector's observation of the process operations can also be useful.

Instrument tampering is a concern when the inspector is using the operator's instrument or when his instrument is left unattended. It is also a matter of concern for the surveillance instruments the inspector might use. Rendering an instrument inoperative for a period of time could allow understatement of measurements or could allow certain operations to be performed without detection by a surveillance device. Introducing a bias to an instrument could allow understatement or overstatement of measurements or of activities observed by surveillance devices. The inspector is particularly concerned that instrument operation not be restored to normal without his knowledge.

One way to protect instruments is by using tamper-indicating sensor modules.[4,13] These tamper-indicating enclosures may be used to protect instrument electronics and sensors and to ensure that instruments are not disturbed during operation.

The inspector also can use calibration checks to monitor instrument performance. If the occurrence of an inspector's recalibration check is known to the operator, and if the inspector is checking only his own standards that have been measured elsewhere, then it is possible for the operator to restore the instrument to normal operation (for example, correct the bias he has been inserting for actual measurements) during the period of the inspector's recalibration check. The inspector can defeat this strategy by means of "running standards." In sample analysis the inspector uses as one of his standards a

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replicate sample previously measured by the operator. The identity of the standard must be unknown to the operator. Thus, if the operator added a bias in the original measurement, the subsequent measurement will not contain that bias because the operator thought he was measuring an inspector's standard.

The operator may also attempt to increase measurement noise; however, artificially increasing the measurement noise provides no advantage and, in fact, will cause a higher false-alarm rate, which the divertor does not want unless he is deliberately trying to discredit the accounting system. Furthermore, the inspector should know the characteristics of the operator's measurement systems if he verifies the operator's measurement control program.

Data tampering presumes that problems related to measurement procedures and instrument tampering have been addressed. Therefore, the next problem is in transmitting data from the instruments to the inspector. The operator may have the same data, and if he wishes to subvert the system, he may try either to change the measurement results at the instrument before they are transmitted to the inspector or to insert false measurement results into the data links. Thus, the inspector's problem is to authenticate both the originator of the data, that is, the instrument, and the data itself. He is not concerned with secrecy of the data.

Cryptographic techniques can deal with the authentication problem in this situation. The general problem of cryptography has been discussed in Refs. 14-16. The evaluation in Ref. 16 concluded that public-key encryption is preferred for safeguards applications. For those unfamiliar with cryptographic techniques, Refs. 14 and 15 outline the concepts of secret-key and public-key cryptosystems, respectively. Implementation of a public-key system does not require inspector input to the operator's instruments but does require access to the output. The operator's ability to use the instrument and acquire data is not compromised.

To address the problem of tampering with measurement error statistics, the inspector will participate in the measurement control program for the safeguards accountability system.

In addition to these specific falsification mechanisms, the inspector might be concerned that the uncertainties for a particular MBA are too large. If it is impractical to make sufficiently sensitive inventory measurements at an adequate frequency to achieve timely detection, it is possible to use surveillance of containment boundary penetrations in conjunction with normal transfer measurements to achieve timely detection for a particular MBA. In the long term, however, the safeguards system's sensitivity to diversion will still depend on the uncertainties associated with transfer measurements because these ultimately dominate.

Finally, to ensure the validity of his verification activities, the inspector must periodically reverify the integrity of the containment boundaries and reverify any aspect of the facility or safeguards system design that may be affected by maintenance.

3. Data Comparison and Evaluation. During this step the inspector has available his verified measurement results in addition to a possibly falsified sequence of correlated operator's materials balances and their associated measurement data. The inspector examines containment/surveillance and other data that he has collected to determine whether any anomaly can be seen in the measurement data or whether there is any other indication of possible diversion. The inspector then combines all available measurement data to permit reliable detection of diversion of material.

Analysis methods are reviewed briefly in Sec. V and Appendix B. Reference 17 and Appendix H of Ref. 3 contain further information on some possible alternatives.

4. Resolution of Anomalies. The details of this activity cannot be defined until specific plant and safeguards systems designs are chosen. However, we can consider the kinds of activities that might take place whenever the Agency is unable to verify the State's findings. This subject has been addressed by the IWG-RPS/Subgroup 4, and a summary of their work appears below.[18]

In the event of an alarm, a number of activities can be undertaken to resolve a situation before a final conclusion is drawn. At each stage it can become apparent that the alarm might be a false alarm, for instance, as new information becomes available. In such a case corrective action could be taken, and the inspector could perform the necessary analyses on the data once more to determine if an alarm were still indicated. The order of events will depend somewhat on the nature of the alarm; with that proviso, the stages would be as follows.

- The inspector would check his instruments, calculations, and data analyses.
- The inspector and operator would consult on the possible reasons for the apparent discrepancies.
- The inspector could refer to other parts of the system providing the alarm, or to other systems to determine if there were any evidence to confirm the alarm hypothesis.
- The inspector could take additional measurements and make additional checks.

- The inspector and operator could consult again to examine the possible reasons for any remaining discrepancies.
- The operator could be requested to take additional measurements, including, in the extreme, a physical inventory.
- The inspector would perform the necessary additional analyses.
- The inspector would state his technical conclusion.

In the event of a systems failure, either accidental or induced, the same iterative investigative procedures would apply as in the case of an alarm. However, the opportunity to take actions short of a physical inventory may well be much more limited in this case. This situation arises because if a system failed it would be important to re-establish knowledge of the inventory for that area. Furthermore, in certain cases such as a failure to measure waste before release, there may be no opportunity to reaffirm the reported measurement data because the material might no longer be available for measurement. Thus, it is important to consider the need for redundant safeguards measures or to ensure that material remains available for possible remeasurement until the inspector is satisfied that the original measurement is valid.

For an accidental failure in the system, the subsequent activities may depend upon whether the failure can be recognized by the divertor. If the divertor cannot recognize and take advantage of the failure, the deterrent value of the system is not lessened though the system's ability to detect particular random attempts to divert is lost.

III. DESIGN APPROACH TO INTEGRATED SAFEGUARDS

The use of materials accounting and containment/surveillance in international safeguards systems for reprocessing plants is the subject of intensive study within the IAEA and by Member States.[2-4,19-23] The structure of the integrated system evolves from (1) assessment of internal and external criteria that must be met, (2) evaluation of the capability of materials accounting and containment/surveillance technology to meet the criteria, (3) consideration of available and projected technology to fulfill systems requirements, and (4) integration of materials accounting and containment/surveillance safeguards features. An integrated system should be cost effective in meeting design criteria with minimal intrusion on process operations. Inspector verifiability of information provided by the system is an important consideration during design and is discussed in Sec. IV.

A proposed approach to designing integrated safeguards systems consists of the following six steps.

(1) Identify safeguards system performance goals.

(2) Examine the operator's accounting system and identify the inspector's key measurement points (KMPs) and safeguards concerns for each MBA.

(3) Define the verification elements to be applied to the KMPs.

(4) Evaluate the verified operator's accounting system in terms of the performance goals.

(5) In MBAs where improved performance is desirable, identify materials accounting and containment/surveillance alternatives for improving performance.

(6) Evaluate the performance of alternative systems.

Each of these steps is discussed in more detail below.

A. Performance Goals

With the assistance of expert advisory groups, such as the IAEA Standing Advisory Group on Safeguards Implementation, the Agency has chosen four measures of performance for safeguards systems: (1) a significant quantity of material (SQ), (2) detection time (T), (3) detection probability ($1 - \beta$), and (4) false-alarm probability (α).

The SQ measure is related to the estimated quantity of nuclear material required for constructing a nuclear weapon. Desirable values of SQ depend on the type of nuclear material; the resultant matrix of significant quantities is given in Ref. 19. It has been suggested that the detection time (T) should be related to the time required to convert diverted nuclear material into a form suitable for constructing a weapon. Estimated conversion times for various materials forms are given in Ref. 19. Desired values for the performance measures SQ and T are still under discussion, although the Agency generally follows the guidelines outlined in this section. The Agency's current attitude is well summarized in a recent paper by Gruemm[24] in which he stated that "these detection goals are not requirements but serve as guidelines for the development of safeguards approaches applicable to generic types of nuclear facilities. . . ."

The Agency considers the possibility of alternative diversion strategies, ranging from abrupt to protracted. Abrupt diversion is defined as having occurred within the estimated conversion time, and the period for protracted diversion is arbitrarily set, usually at one year. The significant quantities are unchanged in either case.

Values of the detection and false-alarm probabilities have been generally set by the Agency at 95% and 5%, respectively, for either abrupt or protracted diversion. It is commonly accepted that a 95% probability of detection is adequate to provide the desired deterrence and assurance. At the same time, the 5% false-alarm probability is deemed small enough that safeguards credibility would not be strained and alarms would occur so infrequently as not to be overly disruptive.

The desire to maximize safeguards systems performance is offset by considerations of process design, operating economics, health and safety, technical safeguards capability, and Agency resources. Materials accounting and containment/surveillance should be integrated in a manner that will allow the most reasonable compromise between safeguards performance goals and these constraints.

B. Safeguards Concerns

As a part of the facility attachment, the operator provides descriptions of the facility, the materials accounting system, and the reports that will be supplied to the Agency. The safeguards system designer's first step is to deduce from this information the relevant safeguards concerns as applied to the selected KMPs. As discussed in Sec. II, some concerns involve the verifiability of key measurements of material inventory and transfers. In determining specific verification requirements for KMPs, the designer should be aware that certain features of process design and operation affect the interface between the materials accounting system and the reprocessing facility.

Each measurement has an impact on the sensitivity of loss detection. Therefore, the impact and the desired quality of that measurement should be evaluated systematically.

In high-throughput processes, the relative accuracy between feed and product measurements limits long-term detection sensitivity.[25,26] Consequently, it is important to control long-term relative biases between feed and product measurements. Theoretically, the limiting factor is the uncertainty in the relative biases between the physical or chemical standards used for these measurements, which may be <0.1%. To approach this limit, sources of long-term measurement bias other than standards must be controlled by careful design of the sampling, measurement, and calibration hardware and procedures (Ref. 11, Part F; Refs. 27-30). Feed and product accountability vessels must be designed for accurate calibration and should be accessible for frequent calibration checks and periodic recalibrations. To meet the Agency safeguards goals, the best applicable sampling and assay methods must be used, and analysts must be carefully trained in the use of calibration and analysis procedures.

In dynamic materials accounting, the precision of the in-process inventory measurements and the variability of any unmeasured holdup are the limiting uncertainties in short-term detection.[26] Tanks and vessels containing significant inventory should be instrumented for on-line measurements. These measurements need not be of high quality; precisions of 1 to 5% are generally adequate for the reference facility. However, even with precise measurements, large buffer-storage tanks may introduce large absolute errors that will seriously degrade the short-term detection sensitivity. Relatively minor holdups and sidestreams will have little effect on detection sensitivity; estimates based on historical data, with appropriate uncertainties, can be used until these components are measured, for example, during a physical inventory.

Process operating modes also affect materials accounting sensitivity. Well-defined input and output batches facilitate accounting; if the process is operated continuously, batch definition requires continuous stream measurements. If there are significant recycle streams between MBAs, input-output correlations will be of limited value. Operating the process in relatively small batch-fed campaigns with a flushout between campaigns helps alleviate these problems.

The effect of in-process inventory on short-term detection sensitivity is minimized by operating the process near steady state. In case of a severe upset, the ability to drain the in-process material into instrumented tanks and recover normal operation will aid materials accounting and control and may extend the time required between physical inventories. During nonroutine operations, such as startup and shutdown, well-characterized "reference states" of the process could be established as fiducials for materials accounting, for example, to estimate inventory changes in contactors (Ref. 3, Appendix J).

Other safeguards concerns may stem from the inability, in certain MBAs, to close materials balances with required sensitivity or frequency when only using available measurement procedures.

C. Verification Elements

Techniques are then developed to provide the necessary verification at each KMP by the inspector. Sufficient independent information must be collected to ensure that materials tampering, instrument tampering, and data falsification cannot occur without risk of detection. Methods for obtaining this information include human or instrumental surveillance of relevant process and measurement operations. Surveillance of containment boundary penetrations may also be used to ensure that undetected bypass of KMPs cannot occur. No systematic approach has been developed to design KMP surveillance. Specific verification techniques that might be applied in the reference facility are discussed in Sec. IV. Having established the fundamental integrity of a sufficient set of measurements, the inspector may then analyze all available measurement information to determine whether diversion has occurred.

D. Evaluation

Once the inspector has sufficient valid data, the effectiveness of the inspector's verification of measurement information may be characterized in terms of detection sensitivity, timeliness of detection, and false-alarm rates. The potential effectiveness of materials balance closures in detecting a diversion is assessed and compared to performance goals agreed upon by the Agency and the State. If, in certain MBAs, materials balances cannot be closed with sufficient timeliness or with sufficiently small uncertainties, alternative or additional safeguards measures may be considered to provide additional assurance that undetected diversion cannot occur.

E. Alternative Safeguards Measures

Two concepts are described in this report that might, if implemented, provide additional safeguards assurance. In MBAs where cleanout and physical inventory sufficiently disrupt process operations to make timely conventional materials balance closure impracticable, in-process inventory measurement or estimation might be used to close materials balances in near-real-time. In this study, this type of system was assumed for the process area and evaluated as an option in the chop/leach and product storage area. If process characteristics preclude timely inventory measurements or estimates, surveillance of containment boundary penetrations might be used to provide assurance that unreported inventory changes cannot occur without risk of detection. In this concept, it is assumed that all nuclear material is enclosed within fixed boundaries. Surveillance is applied to any penetrations of these boundaries that could credibly be used for diversion. This surveillance would detect, virtually in real time, material movement or access to material potentially associated with diversion.

F. Evaluation of Alternative Systems

Once the alternatives for improving safeguards system performance have been identified, they can be considered. Section IV of this report presents an evaluation of safeguards for each MBA. The evaluated concepts would enhance systems performance; however, process impact and economic considerations were not addressed. The methods used for this report allow separate evaluation of the verified materials accounting and containment/surveillance subsystems. A method to provide a combined evaluation has not been developed.

IV. DETAILED CONCEPTS OF INTEGRATED SAFEGUARDS FOR THE REFERENCE FACILITY

A. Introduction

In this section we examine detailed concepts for materials accounting and containment/surveillance in the reference facility that implement the general principles discussed in Sec. II. The discussion of detailed concepts of integrated safeguards is intended only to give an idea of the possible range of measurements, surveillance instruments, and inspector activities. It does not imply that all the elements discussed or listed are essential to an effective safeguards system. The selection of inspector activities, verification measurements, and surveillance instruments will have to be made by the IAEA, after consultation with the facility operator and the State, based on three criteria: (1) minimum interference with process operations, (2) availability of necessary resources, and (3) compliance with safeguards performance specifications.

1. Materials Accounting. A materials accounting system will be established and maintained by the facility operator to conform with State requirements. It is assumed in this report that the operator's accounting system for the reference facility will be a combination of conventional materials accounting and dynamic (or near-real-time) accounting. In conventional accounting strategies, materials balance closure is obtained from the algebraic sum of the measured inputs (positive), outputs (negative), and the in-process inventories obtained from process shutdown and cleanout at the beginning and end of the balance period. Thus, conventional materials balances are closed once during each physical inventory.

Conventional materials accounting may not satisfy reasonable safeguards-effectiveness criteria for plutonium in a high-throughput facility such as the reference facility (15 MT plutonium/yr). Materials accounting and control could be improved if conventional materials accounting measures were augmented by near-real-time materials accounting. In near-real-time accounting, the in-process inventories of major process vessels and columns are measured or estimated to permit frequent closure of materials balances.

2. Surveillance. Two types of surveillance are proposed in the integrated system: surveillance of containment boundary penetrations and surveillance of KMPs. In general, surveillance instruments will be owned, operated, and maintained by the Agency.

An approach to designing surveillance systems for containment boundaries described in Ref. 4 contains the following steps:

(1) selection of containment boundaries,

(2) identification of containment boundary penetrations,

(3) reduction of the number of penetrations by facility and/or containment boundary design,

(4) assessment of the credibility of diversion through specific penetrations,

(5) identification of appropriate surveillance devices for penetrations that are part of credible diversion paths,

(6) identification of performance parameters for surveillance devices, and

(7) quantification of systems performance.

Steps 1, 2, 4, and 5 for each MBA are discussed in this section. Step 3 was not performed for this study because we assumed the design for the reference facility was fixed. Steps 6 and 7 are discussed in Sec. V.

An approach to the design of surveillance monitors for KMPs has not been developed. In the process of designing such systems, scenarios and procedures that could lead to measurement falsification would be identified and evaluated with regard to credibility.

When a containment boundary is selected for surveillance, an attempt is made to identify all penetrations of that boundary and to assess the credibility of diversion through each penetration. Diversion through certain penetrations may be sufficiently difficult or costly that the diversion is not deemed credible. Credibility is assessed by considering the quantity of plutonium that becomes accessible, the fission-product concentration, and the ease of accessibility to plutonium through that penetration. In this study penetrations were placed in two categories: (1) those through which diversion is deemed most credible (Category I) and (2) those through which diversion would require either shutdown and decontamination of the area or major construction, or both (Category II).

3. Inspection Activities. It is assumed that the reference facility will be under continuous inspection and that the inspector will have on-site laboratory facilities to permit verification of some of the operator's analyses by analysis of duplicate samples. The inspector may also make independent measurements and observe selected plant operations, sampling, and measurements to verify that the plant is operating normally, valid samples have been taken, and meaningful measurements are being made. An on-site

analytical capability for the inspector provides the added benefit of rapidly resolving analytical differences between the operator and the inspector.

A description of some of the measurement instrumentation available to IAEA inspectors is given in Appendix A. Many instruments use nuclear techniques that are dependent on gamma-ray or neutron signatures and are therefore isotope-specific. Other techniques, such as x-ray fluorescence, x-ray absorption-edge densitometry, spectrophotometry, and controlled-potential coulometry, are element-specific except for atomic weight corrections. They do not require a knowledge of isotopic composition and are readily applied to determining the plutonium and uranium concentrations in solution.

The inspector should verify the calibration of plant vessels and instruments, and he will be responsible for operating the Agency-owned surveillance instruments and interpreting data associated with surveillance of the operator's measurement procedures and containment boundary penetrations. In addition, the inspector must periodically reverify the integrity of containment boundaries and any aspect of the facility or safeguards systems design that may be affected by maintenance. Finally, the inspector will check the operator's materials accounting data and may independently draw a materials balance for each MBA based upon the independently verified accounting data, for comparison with the balance obtained by the operator.

B. MBA Structure

For conventional materials accounting, the reference facility is divided into four MBAs, shown in Fig. 1. An MBA is generally a physical area where the quantity of nuclear materials moving in or out can be measured. The input, output, and inventory measurement points for these MBAs are called KMPs.

The four MBAs are fuel receiving, storage, chop, and leach (MBA 1); the separations process area (MBA 2); the uranium product storage area (MBA 3); and the plutonium-nitrate storage area (MBA 4). MBAs 1, 3, and 4 are shipper/receiver MBAs, and MBA 2 is a process MBA. MBA 3 (uranyl-nitrate storage) was not considered in this study. For each of the remaining MBAs, the operator's materials accounting system, the safeguards concerns, the surveillance system, and possible inspector verification activities are discussed.

For near-real-time materials accounting, an MBA may be divided into several UPAAs. However, in this study the separations process area (MBA 2) was treated as a single UPAA to eliminate the need for verifying flow KMPs within the MBA.

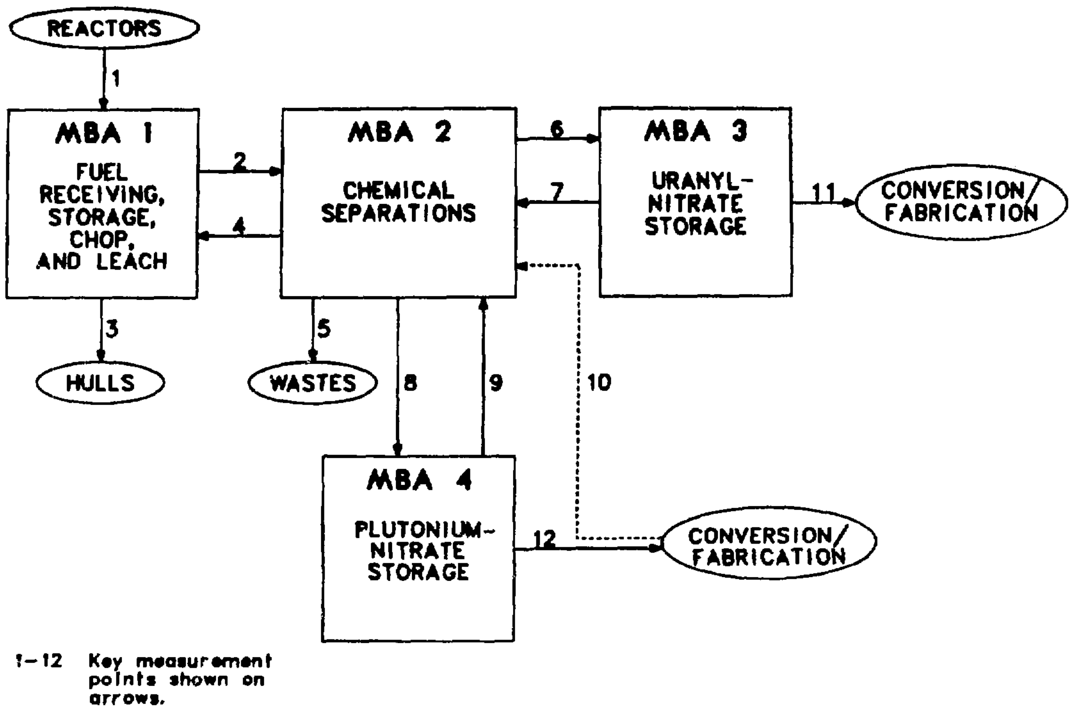

Fig. 1. MBAs for the reference facility.

The KMPs were so chosen because significant quantities of plutonium are present, and/or the material is entering or leaving an MBA. The KMPs will be under Agency surveillance to ensure that meaningful measurements are being made and that no tampering occurs.

C. Safeguards in MBA 1

MBA 1, shown in Fig. 2, includes the cask-unloading and spent-fuel pools, the shearing operation, and the dissolution process. The flow KMPs are :

(1) KMP 1a - cask-unloading pool (receipt of irradiated fuel in MBA 1);
KMP 1b - spent-fuel transfer tunnel (transfer of irradiated fuel to the chop/leach process);
(2) KMP 2 - accountability tank (transfer of dissolved nuclear material from MBA 1 to MBA 2);
(3) KMP 3 - leached-hulls monitor (leached hulls being monitored for residual plutonium and uranium content before they are discarded); and

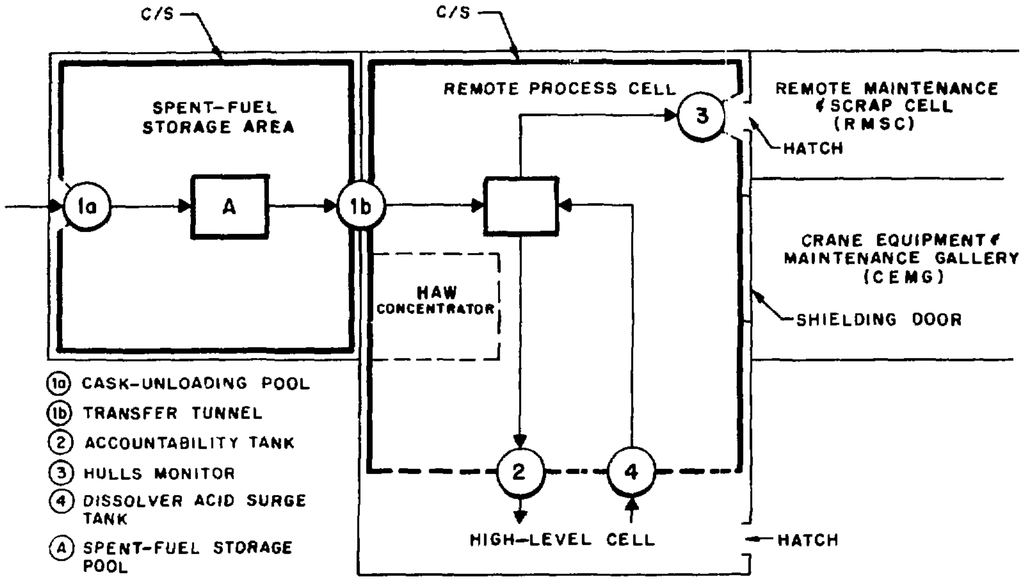

Fig. 2. Schematic of MBA 1.

(4) KMP 4 - dissolver acid surge tank (transfers of recycle acid from MBA 2 to MBA 1).

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

1. Operator's Measurement and Accounting System.

a. KMP 1a, Cask-Unloading Pool. The cask-unloading pool is the first accountability point in the fuel receiving and storage area; all incoming spent fuel passes through this point. Individual fuel assemblies are removed from the shipping cask and are placed in fuel storage baskets. Only at that time and when the assemblies are transferred to the mechanical shearing cell are individual fuel assemblies isolated and available for nondestructive examination.

Irradiated fuel assemblies are discrete units that should be counted and identified. There should be a unique identifier or serial number permanently attached to the supporting structure. The identifier may consist of a tamper-indicating fuel assembly identification device (FAID) that can be interrogated by the operator.[31,32] Generally the serial number of each fuel assembly is read visually and is checked against the accompanying shipping papers.

The shipping papers also include the following data for each fuel assembly:

(1) shipper identification;

(2) date of transfer;

(3) fabricator's data (before irradiation), including chemical composition and total and fissile weight of uranium; and

(4) shipper's data (after irradiation), including burnup, isotopic composition, and total and fissile weight of uranium and plutonium.

The fabricator's data are based on chemical analysis of the fuel material and nondestructive assay (NDA) of the fuel rods. The shipper's data are based on the reactor power history, which is used in calculations, together with the fabricator's data, to obtain the burnup and isotopic composition of the spent fuel.

Nondestructive examination of spent-fuel elements in the fuel unloading and storage area might provide a valuable input measurement for the operator as well as a means of checking the shipper's data. In reprocessing plants now in operation, the input measurement is made only after the fuel has been dissolved and the solution has been transferred to the accountability tank. However, shipper/receiver (S/R) differences could be resolved on receipt of the material instead of following analysis of the dissolver solution. Resolution of S/R differences on the basis of analysis of the accountability tank contents may be complicated by back-cycle streams or heels in the dissolver and accountability tanks and by the difficulty of measuring losses in the leached hulls. Information supplied by NDA measurements could also be used as an aid to criticality control in the dissolver tank and for efficient batch processing of the spent fuel for maximum fissile recovery.

Nondestructive methods for spent fuel have recently been reviewed;[33,34] they are based on measurement of the gamma-ray and neutron signatures of the fission and activation products and the actinide inventory in the spent-fuel assembly. Nondestructive techniques that have been applied by the operator or the inspector to spent-fuel assemblies are listed in Table I. All measurement techniques involve direct measurement of radiations emitted by the irradiated fuel material, except the Cerenkov-light technique that measures secondary radiation. A detailed description of the various nondestructive measurements is given in Appendix A.

b. KMP 1b, Spent-Fuel Transfer Tunnel. Spent-fuel assemblies are transferred from the storage pool to the mechanical shearing cell through the transfer tunnel, which is the last place in the facility where item accounting can occur. Accounting techniques at the transfer tunnel are similar to techniques applied at the cask-unloading pool.

TABLE I

SPENT-FUEL NONDESTRUCTIVE MEASUREMENTS

Measurement Type	Capabilities	Limitations	Reference
Cerenkov light	Radioactive material; rapid; simple instrument; above water; no fuel handling	Nonspecific; self-shielding; semiquantitative; bare assemblies in pool	35
Gross gamma	Gamma-dose rate; axial profiles; simple instruments; minimal fuel handling	Nonspecific; self-shielding; semiquantitative	36,37,38
Gamma spectrometry	Gamma spectra; fission-product specific; exposure and cooling-time correlations; well established	Self-shielding; relatively complex; relatively slow; fuel handling required; geometry-specific	39,40
Passive neutron	Neutron-dose rate; penetrability; exposure correlation; relatively simple; minimal fuel handling	Nonspecific; cooling-time dependence	40,41
Active neutron	Fissile content; penetrability; independent assay	Complex instrument; requires neutron source; fuel handling required; geometry-specific	42,43

c. KMP 2, Accountability Tank. The output product measurement for MBA 1 and the input measurement for MBA 2 are made at the accountability tank. The amount of dissolved nuclear material contained in one batch is determined by (1) measuring the volume of solution in the accountability tank with an electromanometer and (2) measuring uranium and plutonium concentrations and isotopic compositions in samples by isotope-dilution mass spectrometry or chemical analysis. X-ray fluorescence spectrometry may also be applicable to the determination of uranium and plutonium concentrations.[44] Details regarding the techniques used by the operator for the analysis of samples are given in Appendix A. The operator's activities at KMP 2 are discussed further in Sec. IV.D.1.a.

d. KMP 3, Leached-Hulls Monitor. Leached hulls are the major waste product from MBA 1. Approximately 0.1 to 1% of the original fuel may remain undissolved after leaching.[45] A measurement of the fissile content is required for accountability and for process control. If the amount of fuel exceeds ∿0.5% of the fuel value, the hulls are releached.[6] A measurement accuracy of 10-50% is considered adequate for light-water reactor (LWR) reprocessing facilities. Potential measurement methods include passive gamma-ray methods for fission products or passive or active neutron methods for transuranium elements. These methods are discussed in more detail in Appendix A.

e. KMP 4, Dissolver Acid Surge Tank. Recycled acid from MBA 2 is batch-transferred to MBA 1 through the dissolver acid surge tank. At the reference facility, only trace quantities of plutonium are expected to be present in the acid. Uranium and plutonium content of the recycled acid is determined from volume measurements and either fluorometric or spectrophotometric concentration measurements.

f. KMP A, Spent-Fuel Storage Pool. Materials accounting activities associated with the assemblies in the spent-fuel storage pool normally occur only when a physical inventory is taken. During a physical inventory, the operator counts the fuel assemblies and reads the serial numbers of a random sample of assemblies. Additional NDA measurements would be performed only if the assemblies have been stored long enough that their characteristics have changed significantly.

g. Materials Balance Closure. A materials balance may be drawn for MBA 1 when a physical inventory of the contents of the spent-fuel pool is conducted. This balance is obtained by adding the shipper's values (or operator's NDA measurements) for fuel previously in storage (KMP A) and received (KMP 1a) to the operator's values for the corresponding batches of recycle acid (KMP 4) and subtracting the operator's values for the accountability tank (KMP 2), the leached-hull batches (KMP 3), and the shipper's values (or operator's NDA measurements) for fuel presently in storage (KMP A). Uncertainties in the materials balance or S/R difference arise primarily from the input estimates. Comparison of shipper's predictions, obtained from burnup codes, with measurement data shows that the total plutonium content can be predicted with a positive bias of 3-5% and a 1-σ variability of 4-6%.[46]

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

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

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

3. Verification Activities in MBA 1.

a. KMP 1a, Cask-Unloading Pool. To perform his verification duties, the inspector must know when fuel is entering or leaving the facility. A spent-fuel monitoring system will provide a record for the inspector of spent fuel entering the facility. This monitoring system will probably include a combination of radiation detectors and crane monitors in conjunction with optical surveillance.[47]

Two types of nondestructive measurements need inspector verification in the spent-fuel receiving area: (1) rapid qualitative measurements of spent-fuel assemblies (attributes check), and (2) quantitative measurements of a limited number of the fuel assemblies (variables test). The inspection effort is limited by available manpower and by legal constraints. An IAEA Advisory Group on the Nondestructive Measurement of Spent Power Reactor Fuels has recommended six levels of verification (Table II), ranging from verifications of the physical characteristics to measurements of the fissile contents of fuel assemblies.[48] The specific level of verification depends on the available resources and the desired level of assurance.

Characteristics of an irradiated fuel assembly can be stated as follows.

(1) It looks like a spent-fuel assembly with the correct color and identification number.

(2) It is highly radioactive and contains fission products.

(3) Neutrons are emitted by the assembly.

(4) Its activity profile is similar to that of other assemblies of the same type.

TABLE II

LEVELS OF SPENT-FUEL VERIFICATION AND NDA TECHNIQUES

Level of Verification	Technique: Gamma-Ray	Neutron	Other
Physical characteristics	Not applicable	Not applicable	1) Item counting 2) Coloration 3) Mass by weighing 4) Serial number
Physical integrity of fuel assemblies	Gross changes: 1) Comparison of relative intensity of specific high-energy gamma rays 2) Comparison of relative values of measured isotope activity ratios	Gross changes: Comparison of relative neutron emission rate	1) Cerenkov radiation 2) Mass by weighing 3) $Be(\gamma,n)$ 4) Thermoluminescent dosimeter 5) Seals
Indication of irradiation exposure	Simple gross-gamma-ray detection techniques	Simple passive neutron detection techniques	1) Cerenkov radiation 2) Detection of heat 3) Thermoluminescent dosimeter
Presence of fission products or actinides	Low- or high-resolution techniques for detection of Cs-137, Cs-134, Pr-144, and others	Verification of neutron rates expected for declared exposure	$Be(\gamma,n)$
Relative concentrations of fission products or actinides	1) Correlations of ratios to exposure, cooling time, and initial enrichment 2) Consistency of measured and declared values	Passive: Relative exposure values Active: Relative fissile contents	$Be(\gamma,n)$
Determination of nuclear materials content	Correlations between gamma spectrometric results and destructive analyses or theoretical calculations	Passive: Depends on cooling time Active: Requires calibration standards	Not applicable

The inspector can check the identity by reading the serial numbers or by reading FAIDs with a portable reader. To verify the other attributes, the inspector may use one or more of the NDA techniques listed in Table II. The verification confidence level increases with the number of characteristics measured. Selecting the appropriate level of verification must be based on facility limitations, manpower, instrumentation, and the impact on the facility's normal operation. If the inspector uses the operator's instruments, he must verify that those instruments are operating properly.

Cerenkov-light detectors have been adopted by Agency inspectors as a rapid verification technique. Other promising verification techniques are gross-gamma-ray and passive neutron-detection systems. A ring detector that incorporates both a gross-gamma measurement and a neutron measurement has been devised.[49]

In addition to determining that spent fuel passing through the cask-unloading pool is properly accounted for, the Agency must verify that the cask-unloading pool is not bypassed. This verification will be accomplished by providing surveillance of penetrations in the containment boundary surrounding the fuel receiving and storage area that do not correspond to measurement points. Those penetrations are listed in Table III with examples of instruments that could monitor those penetrations.

b. KMP 1b, Spent-Fuel Transfer Tunnel. A rapid verification of fuel assemblies entering the spent-fuel transfer tunnel is used to verify item accounting data for the spent-fuel storage area. Verification activities at this point would be very similar to those in the cask-unloading pool; FAIDs and qualitative or quantitative measurements could be used. Radiation sensors and/or crane monitors coupled with optical surveillance could be used to alert the inspectors that fuel movements are occurring. Monitoring the penetrations listed in Table III will ensure that the spent-fuel transfer tunnel is not bypassed.

c. KMP 2, Accountability Tank. Verification activities for the product output of MBA 1 at the accountability tank are the same as those for the input measurement for MBA 2 and are described in Sec. IV.D.3.a.

d. KMP 3, Leached-Hulls Monitor. The leached hulls normally contain small amounts of plutonium and represent an output from MBA 1. There is some question as to whether the plutonium in the hulls represents a credible source of nuclear material for a divertor. We assume that the plutonium normally in the hulls is not recoverable.

TABLE III

FUEL RECEIVING AND STORAGE AREA PENETRATIONS

Penetrations	Category I Penetrations	Total No. of Penetrations[a]	Surveillance Measures
Cask transport vehicle portals	2	2	Spent-fuel monitoring system
Doors	0	3	Camera[b]
Emergency exits	0	2	Camera
Service headers	0	8	Camera
Sump lines	0	1	Camera
TOTAL	2	16	

[a]Category I plus Category II.

[b]Two or three cameras may be adequate to monitor all doors, emergency exits, service headers, and sump lines.

Overstatement of hulls measurements is not a falsification concern if the limits on allowable plutonium content can be set sufficiently close to normal operating conditions so that the quantity that can be concealed is small compared to detection goals. Overstatement of the hulls' plutonium content requires diversion from some other point in the area. Such a diversion should be detected by other safeguards measures (see Sec. IV.B.3.g).

Although overstatement itself is not a concern, possible concealment of additional material in the hulls as a means of transporting it out of the MBA is a concern because of the large measurement uncertainties in MBA 1. Therefore, the inspector should verify the calibration and operation of the hulls monitor. The inspector should also verify that no additional material is inserted in the hulls cask after measurement by observing the handling of the hulls until they are packaged and leave safeguards.

Another vulnerability is the possible addition to the hulls of material sufficiently purified so that the hulls monitor will not detect its presence. However, this type of material is present only in MBAs 2 and 4, and it is assumed that any removal of material from there to be concealed in the hulls will be detected by the safeguards measures applied in MBAs 2 and 4.

e. KMP 4, Dissolver Acid Surge Tank. This measurement point represents an output from MBA 2 and an input to MBA 1. Because of the safeguards in MBA 2, understatement of the output from MBA 2, and the corresponding input to MBA 1, is not a concern. Also, because very low limits can be placed on material passing through this point in the reference facility, overstatement of this output from MBA 2 is not a concern. Therefore, no verification activities are recommended for this measurement point. In some reprocessing facilities, the recycled nitric acid may contain safeguards significant quantities of plutonium. In that case, the inspector must verify the volume measurement and determine the plutonium concentration on samples by independent measurement.

f. KMP A, Spent-Fuel Storage Pool. Accounting activities associated with the assemblies in the spent-fuel storage pool normally occur only when a physical inventory is taken. During a physical inventory, the inspector will verify that all assemblies have been counted or accounted for. The inspector may also verify the identity and other characteristics of a random sample from a fuel assembly using the techniques described in Sec. IV.C.3.a.

The degree of safeguards assurance associated with the inspector's inventory-verification activities depends on the frequency of physical inventories in the pool area. If inventories cannot be done with sufficient frequency because of operational constraints, the penetration-monitoring instrumentation discussed in connection with KMPs 1a and 1b can also provide assurance that undeclared removal of spent fuel could not occur without risk of timely detection. It is possible to rely on this assurance for timely detection and extend the time between physical inventories.

g. Surveillance of Containment Boundary Penetrations in MBA 1. The containment/surveillance system associated with the spent-fuel storage area has already been described in conjunction with KMPs 1a, 1b, and A. Surveillance of containment boundary penetrations for the chop/leach section of MBA 1 also is needed because of the large measurement uncertainties in MBA 1 and the possibility of bypassing KMP 2 (the accountability tank).

For areas such as MBA 1 where the measurement uncertainties are large relative to detection goals, diversions within the limits of error of MUF are a concern.

Penetration-monitoring systems would be potentially sensitive to removal of dissolved fuel in the chop/leach area. Although the diversion of dissolved fuel may be deemed incredible because of difficulties in handling highly radioactive materials, it may be possible to remove material from the chop/leach area and insert this material into MBA 2 for processing without measurement at the accountability tank. Process material could then be removed from MBA 2 without appearing as MUF when the material balance is closed. Bypassing feed material around MBA 2 would also be detected with the chop/leach penetration-monitoring system.

The containment boundary selected for MBA 1 is divided into two parts to be monitored, one surrounding the spent-fuel storage area and one surrounding the chop/leach area, as shown in Fig. 2. This division is made because it may be difficult to detect dissolver solution from the chop/leach area moving through the vehicle portals and other fuel-receiving and storage area penetrations. Therefore, the transfer tunnel is treated as a penetration in the chop/leach area containment boundary.

The containment boundary for the chop/leach area consists mainly of the concrete shielding that surrounds the area. Because the boundary between MBAs 1 and 2 is in the middle of the high-level cell, a containment boundary associated with the process piping was drawn to KMPs 2 and 4 between the MBAs. This boundary divides the vessels in the high-level cell that are in MBA 1 from the vessels that are in MBA 2. The hatch to the high-level cell will be sealed to ensure that no additional pipes crossing this boundary are constructed.

In Fig. 2, the crane equipment and maintenance gallery is assumed to be outside the containment; that is, the large shielding door separating the remote process cell from the crane equipment and maintenance gallery is closed and sealed. If this door is opened for maintenance purposes, provisions must be made to monitor the crane equipment and maintenance gallery until the door is resealed. Monitoring could be provided by inspectors or portable equipment, for example, radiation monitors and cameras.

The high-activity waste (HAW) concentrator and associated equipment in the remote process cell are assumed to be outside containment. To ensure that material is not transferred to the HAW concentrator, the inspector must observe equipment passing into the remote process cell to prohibit the introduction of specially designed jumpers.

All penetrations of the containment boundary that could possibly be used for bypassing the output KMPs are identified in Table IV. The table includes the penetrations associated with input KMPs 1b and 4, and lists examples of surveillance instruments that could monitor the penetrations. The surveillance measures identified in Table IV are

TABLE IV

PENETRATIONS OF CHOP/LEACH CONTAINMENT

Penetrations	Category I Penetrations	Total No. of Penetrations[a]	Surveillance Measures[b]
Airlift air supply lines	24	32	LIL
Air/nitrogen purges	0	17	LIL
Air-sparge lines	4	9	LIL
Cold-chemical lines	1	3	PRM
Cooling water lines	0	5	PRM
Decontamination lines	0	7	PRM
Doors	0	1	S
Hatches	0	5	S
Instrument lines	33	66	LIL
K-plugs	0	11	S
Light-blocks	0	15	S
Mechanical connections	0	17	S
Off-gas lines	0	6	LIL
Process lines	0	3	PRM
Sample lines	16	16	SMSI
Shielding windows	0	6	S
Spares	0	45	S
Steam lines	13	21	PRM
Steam/air/water connections	23	31	PRM
Sump lines	2	4	PRM
Transfer tunnel	1	1	RM
Ventilation lines	0	5	LIL
Water lines	3	5	PRM
TOTAL	120	331	

[a]Category I plus Category II.

[b]LIL = liquid-in-line sensor
PRM = pipe radiation monitor
RM = radiation monitor
S = seal
SMSI = sample-monitoring system.

relatively straightforward, with the exception of the sample-monitoring system. This system is needed to ensure that material is not drawn into the sample and analytical cell and routed into vessels in MBA 2, thus by-passing the MBA 1 output measurements. It is assumed that this system would consist of monitors on the sample lines to evaluate materials flowing through the lines, but a precise configuration for the system was not determined. Sensor requirements for all of MBA 1 are summarized in Table V.

h. Verification of the Materials Balance. The inspector may verify the shipper's values for spent fuel if he is able to perform NDA measurements on the fuel assemblies in the cask-unloading pool. If he is unable to perform NDA measurements routinely, the inspector may use isotopic-correlation techniques for verifying the input into the reprocessing facility. The relationship used is

Pu at input = final Pu/U ratio x (initial U - burnup) .

TABLE V

SUMMARY OF SENSORS IN MBA 1

Sensor	Sensors for Category I Penetrations	Total No. of Sensors[a]
Cameras	0	3
Liquid-in-line sensors	61	135
Pipe radiation monitors	42	79
Radiation monitors	1	1
Sample-monitoring system	1	1
Seals	0	100
Spent-fuel monitoring system	2	2
TOTAL	107	321[b]

[a]Category I plus Category II.

[b]There are fewer sensors than penetrations (321 vs 347) because 3 cameras are observing all the penetrations listed in Table III that require cameras, and the sample-monitoring system is observing 16 sample lines.

The amount of uranium and its enrichment at fabrication must be accurately known and verified. The final plutonium-to-uranium ratio in the dissolver solution is independently measured by the inspector or certified by means of heavy-element isotopic correlations. The burnup can be calculated from neodymium isotopic data obtained by isotope-dilution mass spectrometry of dissolver solution, or from semiempirical formulas that involve the plutonium-to-uranium ratio, the final uranium and plutonium isotopic compositions, and the initial uranium enrichment. Reference 3 gives a more detailed discussion of using isotopic-correlation techniques in a reprocessing facility.

The inspector can verify the S/R differences for MBA 1 by comparing the plutonium value at input (obtained above) with the sum of the measurements of the plutonium content in the accountability tank, leached hulls, and flushes.

D. Safeguards in MBA 2

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

(1) KMP 2 - accountability tank; transfers dissolved nuclear fuel to MBA 2 from MBA 1.

(2) KMP 4 - dissolver acid surge tank; transfers recycled acid to MBA 1.

(3) KMP 5a - high-level liquid-waste sample tank.
KMP 5b - general process-waste check tank.
KMP 5c - solid-waste assay station.
KMP 5d - solvent-burner feed tank.
KMP 5e - central stack.

(4) KMP 6 - uranium product sample tank; transfers uranyl-nitrate product from MBA 2 to MBA 3.

(5) KMP 7 - uranium rework tank; recycles off-specification uranyl nitrate from MBA 3 to MBA 2.

(6) KMP 8 - plutonium product sample tank; transfers plutonium-nitrate product solution to MBA 4.

(7) KMP 9 - plutonium product recycle tank; recycles off-specification plutonium nitrate from MBA 4 to MBA 2.

(8) KMP 10 - transfers to MBA 2 from the conversion process.

KMP 4 was discussed in MBA 1, and KMP 10 will not be considered.

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

For near-real-time materials accounting, measurements or estimates must be made at the following strategic points: centrifuge, HA feed tank, HA contactor, HS column, 1B column, 1BX column, 2A column, 2B column, 3A column, 3B column, 3PS wash column, 3P concentrator, and plutonium catch tank.

1. Operator's Measurement and Accounting System. In general, measuring nuclear material into or out of the separations MBA involves measuring solutions in discrete batches, the only exception being the solid waste from maintenance and other activities. Typically, for conventional accounting, a "batch" of liquid is transferred into a measurement tank, thoroughly mixed, the liquid's volume and density measured, the liquid sampled and analyzed, and then transferred. The nuclear materials content of the "batch" is calculated from the measured volume of liquid transferred out of the tank (obtained from the difference in volume before and immediately after the transfer) and the results of the sample analysis.

A common sequence of measurements for determining the nuclear materials content of reprocessing plant solutions follows.

(1) A batch identification number is assigned.

(2) An initial "before receipt" bulk measurement is obtained from readings of the level, density, and temperature of the liquid in the tank.

(3) The batch to be measured is transferred into the tank.

(4) The solution is mixed for the prescribed length of time.

(5) A set of instrument readings is recorded and designated as "before sampling" values.

(6) The solution is sampled using established parameters for sample circulation.

(7) Density and acid values are reported by the laboratory.

(8) A set of instrument readings is recorded and designated as "after sampling" values.

(9) The solution is transferred to the next step in the process.

(10) A set of instrument readings is recorded and designated as "after transfer" values.

(11) The quantity transferred is calculated from the "after sample" reading, the "after transfer" reading, and the laboratory results.

For near-real-time materials accounting, the current volume of liquid in the vessel and an on-line analysis, or concentration estimate, are used to calculate the in-process inventory. On-line instrumentation at the reference facility has been described.[50]

Volume and density measurements of solutions in process vessels and sampling of solutions for analysis are required at most measurement points. These operations are described first, followed by a discussion of measurements specific to a given KMP.

The volume and density of liquid in a process vessel is measured with a dip-tube pneumatic bubbler system. Recent results have shown that the accuracies of volume and density measurements approach 0.1% and 0.2% relative, respectively.[51] The accuracy of volume and density measurements is dependent on

- accuracy of tank calibration and assigned probe separation value;
- accuracy of differential pressure measurements;
- proper application of temperature corrections;
- constancy and balancing of bubbler air flow;
- assurance that submerged probes are clear (not partially plugged), covered by solution, and probe growth (because of salt crystallization) has not occurred;
- absence of leaks or restrictions in pressure-sensing lines; and
- maintenance of batch integrity.

Density measurements are also made in the laboratory using a vibrating tube densimeter with a maximum accuracy of 0.06%. Density measurements are made in the laboratory on solutions from KMP 2 (accountability tank), KMP 6 (uranium product sample tank), KMP 8 (plutonium product sample tank), and KMP 9 (plutonium product recycle tank).

Before a laboratory sample is removed for density measurement, the solution must be thoroughly mixed to attain homogeneity. Several methods of mixing are used, such as air sparging, airlift circulation, and pumped circulation. Mixing operations must cease during the volume or density measurement.

Measuring sample composition requires obtaining a sample representative of the bulk composition. The following are sampling requirements.

(1) The composition and characteristics of the samples and bulk material must be identical.

(2) The bulk material must be homogeneous throughout.

(3) The composition and characteristics of the sample must not be altered during the withdrawal or in subsequent handling prior to analysis.

Liquid samples are obtained from process vessels and streams by a closed-loop vacuum-assisted airlift sample system and remote needle samplers. The length of the sample lines, elevation, and sample composition all affect the operation of a sampler. To ensure that a sample is representative of the process fluid being sampled, each sampler must be tested to establish its operating parameters. The following factors will result in unrepresentative samples:

- inadequate mixing,
- inadequate sample recirculation,
- dilution of sample, and
- contamination of sample.

Flow measurements of process streams may be required for determining the in-process inventory for near-real-time materials accountability. A measurement precision of 1% or better is required in major process streams, but a 5-10% measurement precision is acceptable for waste streams. Flow meters should be capable of periodic recalibration and preferably should not contact the process fluid. Details of near-real-time materials accounting and flow measurements are discussed in Ref. 3.

Following are possible operator measurements for conventional materials accounting at those KMPs in MBA 2 where appreciable quantities of plutonium may be present.

a. KMP 2, Accountability Tank. The measurements made at this point define the input to MBA 2. The nitric-acid dissolver solution nominally contains 300 g uranium/L and 3 g plutonium/L, along with other actinides and fission products. The plutonium content of the input accountability tank can be measured using the gravimetric or the volumetric method.

(1) Gravimetric Method. For the gravimetric method the plutonium content of the accountability tank is obtained by correlating the uranium-to-plutonium ratio measured from accountability tank samples to the fissile content of the original fuel. Accurate knowledge of the original fuel composition is required; however, a volume measurement of the accountability tank is not necessary. The uranium and plutonium content of the accountability sample can be measured using mass spectrometry. Alternatively, the uranium-to-plutonium ratio can be measured using x-ray fluorescence spectrometry[44,52-58] or electrometric titration methods as described in Ref. 59.

(2) Volumetric Method. For the volumetric method the plutonium content of the accountability tank is obtained from measuring plutonium concentration in the solution

and measuring tank volume. Plutonium concentration can be measured using isotope-dilution mass spectrometry, x-ray fluorescence, or the electrometric methods. The volume of the accountability tank is measured with a dip-tube pneumatic bubbler system such as described in Appendix A.

b. KMP 5a, High-Level Liquid-Waste (HWW) Sample Tank. The concentrated high-level waste will nominally contain 3 g uranium/L and 0.1 g plutonium/L, with other actinides and fission products. Isotope-dilution mass spectrometry is used for the determination of uranium and plutonium concentration. Tank volume is measured using a dip-tube pneumatic bubbler system.

c. KMP 5c, Solid-Waste Assay Station. Solid wastes leaving MBA 2 are assayed by NDA techniques, such as gamma-ray or neutron coincidence measurements.

d. KMP 6, Uranium Product Sample Tank. The product uranyl-nitrate solution contains 370 g uranium/L in dilute nitric acid. Uranium concentration can be measured using the potentiometric Davies and Gray/New Brunswick Laboratory (NBL) procedure,[60,61] controlled-potential coulometry in a sulfuric acid medium, or gravimetry. Volume is measured using a dip-tube pneumatic bubbler system. Uranium concentration can be estimated rapidly by measuring the density, acidity, and temperature of the solution. The uranium concentration is then calculated by means of an empirical equation.[62,63]

e. KMP 7, Uranium Rework Tank. Uranyl-nitrate product that does not meet specifications is returned to MBA 2 for reprocessing. Uranium concentration is determined using the potentiometric Davies and Gray/NBL procedure or controlled-potential coulometry. Volume is measured using a dip-tube pneumatic bubbler system.

f. KMP 8, Plutonium Product Sample Tank. The plutonium-nitrate product solution contains 250 g plutonium/L in ∿3 $\underline{N}$ nitric acid. The plutonium concentration is determined by controlled-potential coulometry or by amperometric titration. X-ray absorption-edge densitometry is being investigated as an on-line or at-line measurement.[50,58,64,65] For rapid in-line measurement, the plutonium concentration can be estimated from the density, acidity, and temperature of the solution in the same manner as was the uranium product solution. Volume is measured using a dip-tube pneumatic bubbler system.

g. KMP 9, Plutonium Product Recycle Tank. Plutonium-nitrate product solution that does not meet specifications is returned from MBA 4 for recycling. The plutonium concentration is determined either by controlled-potential coulometry or by an amperometric titration. Volume is measured using a dip-tube pneumatic bubbler system.

h. KMP B1, Feed Adjustment Tanks. Dissolver solution having nominal concentrations of 300 g uranium/L and 3 g plutonium/L in the two feed adjustment tanks is measured using isotope-dilution mass spectrometry. Other methods as described under KMP 2 (the accountability tank) could be used. Volume is measured using a dip-tube pneumatic bubbler system.

i. KMP B2, IBP Surge Tank. The solution in this tank contains 10 g uranium/L and 5 g plutonium/L. The plutonium concentration is determined by controlled-potential coulometry or amperometric titration. Alternatively, both uranium and plutonium can be determined by x-ray absorption-edge densitometry or x-ray fluorescence.

Additional inventory measurement points are used only when the process line is cleaned and flushed into tanks that have been calibrated so that reliable volume measurements can be made and samples can be taken for analysis. The quantities of plutonium expected in these tanks during physical inventory are small, the largest quantity being about 0.9 kg in the plutonium rework tank.[6] Volume is measured using a dip-tube pneumatic bubbler system.

j. Materials Balance Closure. A physical inventory in MBA 2 includes a shutdown and flushout of the separations process area, a cleanout of extraneous samples, and a piece-count verification of remaining materials in the laboratory. For conventional accountability, a materials balance is drawn after each physical inventory by adding all measured receipts (KMPs 2, 7, 9, and 10) to the initial inventory and subtracting all measured removals (KMPs 4, 5, 6, and 8) and the final inventory.

For near-real-time accountability, MBA 2 can be treated as a single accounting area if measurements of the in-process inventory are made on each of the major process vessels in the process area. In-process inventory measurements can be combined with flow KMPs 2, 4, 5, 6, 7, 8, 9, and 10 to form a dynamic materials balance approximately every 2 days. Because most of the material is transferred through the feed and product KMPs, the frequency of taking materials balances is governed by the feed and product batch frequencies. Smaller batches, for example, waste batches to high-level waste, are included in the materials balances when the measurements become available.

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

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

Understatement of inputs for the accountability tank and the plutonium product recycle tank could result from improper measurements. The first opportunity for understatement occurs when the material is transferred into or out of the tank. Understatement could occur if some material flows through the vessel from the output stream(s) before the complete sequence of measurement activities is performed.

Input understatement also can result through understating level and density measurements. The level could be understated if material is drawn up into lines connected to the vessel. Although it might be obvious if material were drawn into the level and density lines, material could be drawn into air-sparge, hose-connection, or cold-chemical and sample lines. Density measurements could be understated by injection of air into the solution during measurement. Transfers could be understated by overstating the heel, for example, by injecting air into the heel. Other factors that could lead to erroneous results in the level and density measurements are listed in Sec. IV.D.1.

b. Output Measurements. Outputs in MBA 2 include recycle to MBA 1, product transfers to MBAs 3 and 4, and waste. Output measurements in which overstatement is of particular concern are from the HWW sample tank and plutonium product sample tank.

Overstatement can be accomplished by manipulating materials transfers, but in a different way than for understatement. Overstatement can result if material remains in a vessel to be measured a second time. This could occur if, while the vessel is being emptied, material is drawn into other lines connected to the vessel and returned to the vessel at the next measurement. These lines should be monitored to ensure that this does not occur.

Concerns related to mixing and sampling as well as level, density, and temperature measurements are similar to those described previously. In this case, however, there is a concern that bubbling air into the vessel during the level measurements that are made just before transfer out may yield high readings. Therefore, the air-sparge lines and other lines that could be used to inject air should be monitored for air flow. Understating level measurements of the heel could result in overstatement of the transfer.

Overstating waste measurements is a concern when the measurement limits cannot be set sufficiently close to zero so that repeated overstatement will not result in a significant amount of material being available for diversion. This may be the case for solid-waste drums containing low-level waste. Other output measurements at the general process-waste check tank (KMP 5b), the solvent-burner feed tank (KMP 5d), and the central stack (KMP 5e) may not require verification because only trace amounts of plutonium are present at these points during normal operations.

c. Inventory Measurements. Overstatement is a concern at inventory measurement points in the

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

Measurements at these points are used to estimate the in-process inventory for near-real-time materials accounting. Points 3-11 are considered as strategic points, but not KMPs. Diversion of material at these points is not as great a concern as at the input and output KMPs because process constraints limit the amount of material that could be contained in these columns and because removal of material would tend to result in column or process upset.

The concerns regarding mixing, sampling, and measurements in tanks are similar to those described for output measurements. However, because concentration limits can be set for normal operations, any overstatement of the quantity of plutonium present is limited by the volume of the vessel. As long as inventory measurements are obtained simultaneously, manipulation of transfers among the inventory KMPs is not a concern; an overstatement at one point, caused by leaving material in a vessel for remeasurement, will result in corresponding understatement elsewhere, and no net effect on the inventory difference will result.

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

Other measurements are made only during physical inventories when the process line is cleaned out and flushed. Negligible quantities of uranium and plutonium should occur in the

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

Verification of measurements at these points is generally not required.

3. Verification Activities in MBA 2. The inspector's verification activities in MBA 2 are concerned with accurate volume, density, concentration, and for near-real-time accounting, flow measurements.

Tank calibration verification is of particular concern for input and output accountability tanks. The accuracy of the tank calibration and the assigned probe separation value can be verified by witnessing and evaluating multiple calibration passes to ensure the correct relationship between liquid level and volume. The relationship applies only to the specific tank for which it was obtained. The Agency inspector may witness the initial calibration of the differential pressure instruments. If the inspector has an independent readout device or calibrating device that is connected to the pressure transducers to be calibrated,[51] he may compare his readings with the operator's readings or perform independent calibrations.

The inspector can verify the calibration of operator's differential pressure instruments by

- using redundant tamper-resistant instruments,
- applying tamper-indicating devices to operator's instruments,
- manifolding a few inspector-owned instruments to a series of operator instruments for periodic checks, and/or
- observing random checks of operator instruments.

Verification of temperature readings could be handled by methods similar to the third and fourth methods described above for pressure transducers. The inspector may have a few temperature recorders that can receive signals from several vessels, but otherwise, random checks may be appropriate.

The inspector must ascertain that solution is circulated through the sampling loop for a sufficient period to ensure that the samples are reproducible and representative of the bulk solution in the tank. Verification of an adequate circulation time may be obtained by comparing density measurements of several successive samples with each other and with in-tank density measurements. The inspector may verify that the solution was circulated for the minimum established time by direct observation or by flow monitors.

The inspector may request duplicate samples to analyze in his laboratory or to submit to the operator's laboratory as blind samples. Analysis must be based on a statistically sound variables sampling plan. Submitting of samples to the operator's laboratory can be effective only if the laboratory does not know and cannot trace the identity of the samples. Such samples may be used to assess the accuracy and precision of an analytical method. A discussion of some analytical techniques available to the inspector is given in Appendix A.

<u>a. KMP 2, Input Accountability Tank.</u> The inspector must verify the operator's accountability tank measurements. For the gravimetric procedure, the original fuel fabricator's data must be verified so that they can be correlated with the uranium and plutonium concentration measurements in the accountability tank. For the volumetric procedure, the plutonium and uranium concentration measurements and the volume measurements (for example, the operator's liquid-level and density measurements) must be verified. The uranium and plutonium concentration may be verified by preparation of

resin-bead samples[66] that are submitted to the operator or transferred to the Agency laboratory for mass spectrometric analysis. The inspector may also measure the uranium-to-plutonium ratio by a rapid method such as x-ray fluorescence spectrometry[52-58] or determine the plutonium concentration by a simple spectrophotometric method.[67]

The accountability tank's complexity requires that a series of operations be performed sequentially to ensure proper tank operation, mixing, sampling, and analysis. The accountability tank is located in the high-level cell (HLC) shown in Fig. 3. The valve pot is connected to the piping and instrument gallery (TPIG). The plutonium product recycle tank is not shown, but has the same configuration.

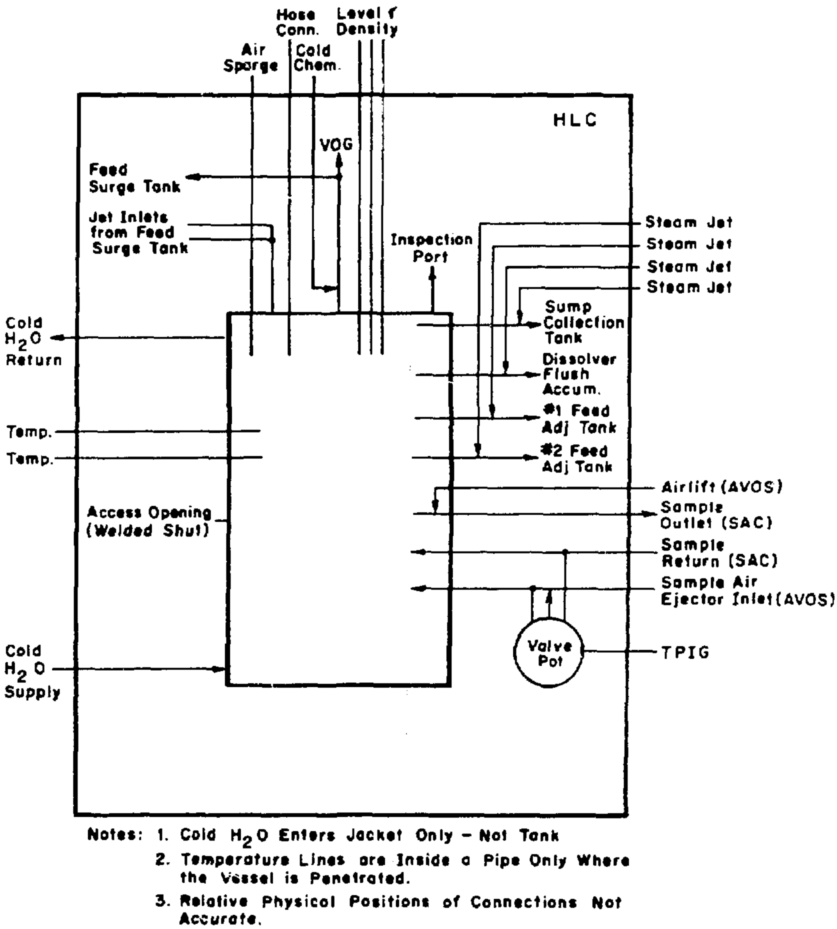

Fig. 3. Schematic of input accountability tank.

Sensors proposed to monitor the accountability tank (shown in Table VI) are typical of those that may be needed at an input measurement point. They include liquid-in-line, radiation, or flow monitors on various lines that could be used to draw material out of the tank during level measurements.

The monitors may have to be placed inside the cell close to the tank to be effective. An alternative to these monitors would provide siphon breaks on some lines. The applicability of siphon breaks would depend upon the function of the line, the ability to make a siphon break tamper-safe, and the feasibility of inserting a flexible pipe within the line to negate the siphon break.

Purge air flow monitors, as well as independent pressure monitors, are identified for verifying level and density measurements. Other monitors shown are used to determine that the proper sequence of steps has been followed during the measurements.

TABLE VI

SENSORS PROPOSED FOR THE ACCOUNTABILITY TANK

Lines	No. of Lines	Sensors
Jet inlets	2	Steam jet, flow, liquid-in-line, or radiation monitors
Jet outlets	4	Steam jet, flow, liquid-in-line, or radiation monitors
Air sparge	1	Air flow monitor and liquid-in-line or radiation monitor
Hose connection	1	Liquid-in-line or radiation monitor
Cold chemical	1	Radiation monitor
Vessel off-gas (VOG)	1	Liquid-in-line monitor
Level and density	3	Pressure monitor, purge air flow monitor
Sample system	4	Circulation monitor and liquid-in-line or radiation monitors

Total number of sensors = 19

A data processing system will be required to correlate the data from various sensors to verify that operations are being carried out in proper sequence. A possible role of the data processing system (DPS) for the accountability tank is described below.

(1) The DPS receives a signal indicating that an input line(s) is in use.

(2) The DPS verifies that output lines are not in use and confirms that they remain off until Step 10.

(3) The DPS receives a signal indicating that mixing is occuring and verifies that the air flow rate and mixing time exceed minimum values.

(4) The DPS verifies that input lines are not used from the time the mixing begins until the transfer is complete.

(5) The DPS monitors level and density calibrations with independent pressure transducers and determines that purge air flow is balanced.

(6) The DPS verifies that no material is drawn into air-sparge, hose-connection, cold-chemical, off-gas, or sample lines during level measurements.

(7) The DPS receives a signal that sample circulation has begun and verifies that the flow rate and circulation time exceed minimum values.

(8) The DPS verifies that the time between mixing and sampling is not excessive.

(9) The DPS observes level and density measurements as in Step 6.

(10) The DPS receives a signal indicating that an output line(s) is in use and verifies that no input lines are in use.

(11) The DPS observes that output line use is completed and continues to verify that input lines are not in use until the heel measurement is completed.

(12) The DPS repeats Step 5 and verifies that no air is being injected into the heel during level measurements.

No attempt was made to establish the credibility of using any lines connected to the accountability tank to understate the measurement. Presumably, these lines could be categorized in the same manner as containment boundary penetrations. If Category II lines were not safeguarded, the number of sensors would probably be reduced significantly.

b. <u>KMP 5a, High-Level Liquid-Waste Sample Tank</u>. The inspector must verify the volume and concentration measurements on high-level liquid waste to ensure that the operator has not overstated his measurement results. The inspector's techniques will be similar to those described for KMP 2 if the plutonium content exceeds acceptable limits.

c. KMP 5c, Solid-Waste Assay Station. Barrels containing low-level solid waste should be checked to prevent overstatement and to ensure that they are not being used to conceal the diversion of plutonium. Barrels could be examined with a segmented gamma scanner[68] or thermal-neutron coincidence counter.[69]

d. KMP 8, Plutonium Product Sample Tank. Verification activities are similar to those described for KMP 2. The plutonium concentration may be verified by x-ray densitometry,[58,64,65] x-ray fluorescence,[53-56] or gamma-ray spectrometry.[70,71] A schematic of the plutonium product sample tank is shown in Fig. 4, and possible sensors are summarized in Table VII. A possible role of the DPS for the accountability tank is described below.

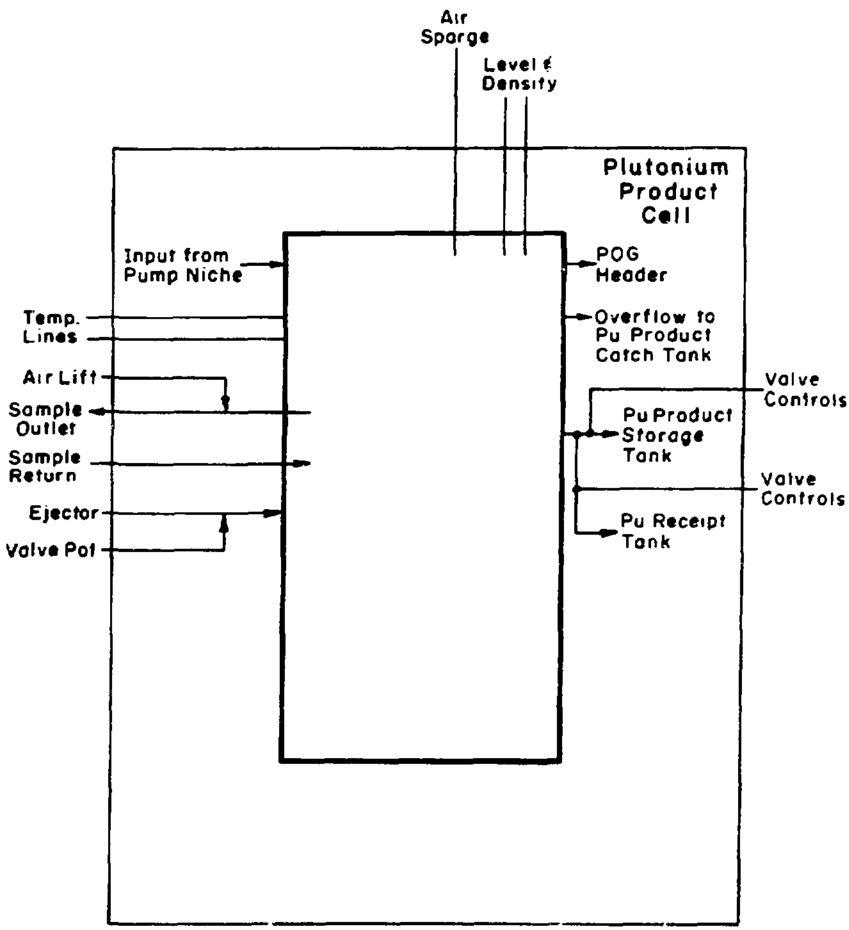

Fig. 4. Schematic of plutonium product sample tank.

TABLE VII

SENSORS FOR THE PLUTONIUM PRODUCT SAMPLE TANK

Lines	No. of Lines	Sensors
Inputs	1	Pump, flow, liquid-in-line, or radiation monitors
Outputs	2	Valve, flow, liquid-in-line, or radiation monitors
Air sparge	1	Air flow monitor and liquid-in-line or radiation monitor
Off-gas	1	Liquid-in-line monitor
Overflow	1	Liquid-in-line monitor
Sample system	3	Circulation monitor and liquid-in-line or radiation monitors and air flow monitors
Level and density	2	Pressure monitor, purge air flow monitors

Total number of sensors = 16

(1) The DPS receives a signal indicating that mixing is occurring and verifies that the air flow rate and mixing time exceed minimum values.

(2) The DPS verifies that input lines are not used from the time the mixing begins until the transfer is complete.

(3) The DPS monitors level and density calibrations with independent pressure transducers and determines that purge air flow is balanced.

(4) The DPS verifies that no air is being bubbled into the vessel during level measurements.

(5) The DPS receives a signal that sample circulation has begun and verifies that the flow rate and circulation time exceed minimum values.

(6) The DPS verifies that the time between mixing and sampling is not excessive.

(7) The DPS observes level and density measurements as in Step 4.

(8) The DPS receives a signal indicating that an output line(s) is in use and verifies that no material is drawn into air-sparge, off-gas, level and density, or sample lines.

(9) The DPS observes that use of the output line is completed and continues to verify that input lines are not in use until the heel measurement is completed.

(10) The DPS repeats Step 5 and verifies that no air is being injected into the heel during level measurements.

e. KMP 9, Recycle of Off-Specification Plutonium Nitrate from MBA 4 to the Plutonium Product Recycle Tank. The inspector must verify the volume and plutonium concentration measurements in the plutonium product recycle tank to ensure that the quantity of plutonium going back into the separations process has not been understated. The verification techniques will be similar to those given for KMP 2. The inspector may wish to know the history of the material and the reasons why it is being recycled. The inspector may compare his analysis of the recycle material with his analysis of the original product material, taking radioactive decay into account.[72]

f. In-Process Inventory Measurements. For near-real-time accounting, verification of measurements at strategic points such as major process tanks and columns is required. To guard against overstatement, the inspector should verify the volume and concentration measurements at KMP B1 (the two feed adjustment tanks) and KMP B2 (the 1BP surge tank). The techniques used at KMP B1 will be similar to those described for KMP 2 (the accountability tank). The uranium and plutonium concentrations at KMP B2 can be verified by x-ray L-edge densitometry or x-ray fluorescence. Verification of the in-process inventory in the HA feed tank will be similar to that at KMP B1. The plutonium concentration in the 3P concentrator (volume is constant) may be verified by the same techniques as those used in KMP 8 for plutonium-nitrate product solution.

Verification of in-process inventories in the HS, 1B, 2A, 2B, 3A, 3B, and 3PS columns requires access to flow and in-line concentration measurements of streams entering and leaving those columns. As noted previously, these verification activities are not of the same significance as verification of input and output transfer measurements, and concentrations can be obtained from installed in-line density measurements. The inspector may observe the operator's measurements and may have independent readout devices that are connected to the operator's transducers. If the inspector has access to flow and concentration measurements, he can use the techniques for contactor in-process inventory estimation discussed in Ref. 3, Appendix J. The inspector will need to observe the operator's volume calibration of the columns; he may wish also to verify the volume and nuclear materials content of the aqueous and organic phases, which are dumped from a column operating at steady state, to improve the quality of his estimates.

The inspector will need to verify that no material is removed from the columns except by the measured process streams. In general, removal of more than a minimal quantity of material will disrupt steady-state operation of a column and will be readily apparent from the other verified measurements.

The 1BP surge tank is shown in Fig. 5 and possible sensors are listed in Table VIII. These sensors are typical of those required at tank inventory measurement points. A possible role of the data processing system here is the same as described for the plutonium product sample tank (KMP 8) except that Steps 8, 9, and 10 are not required.

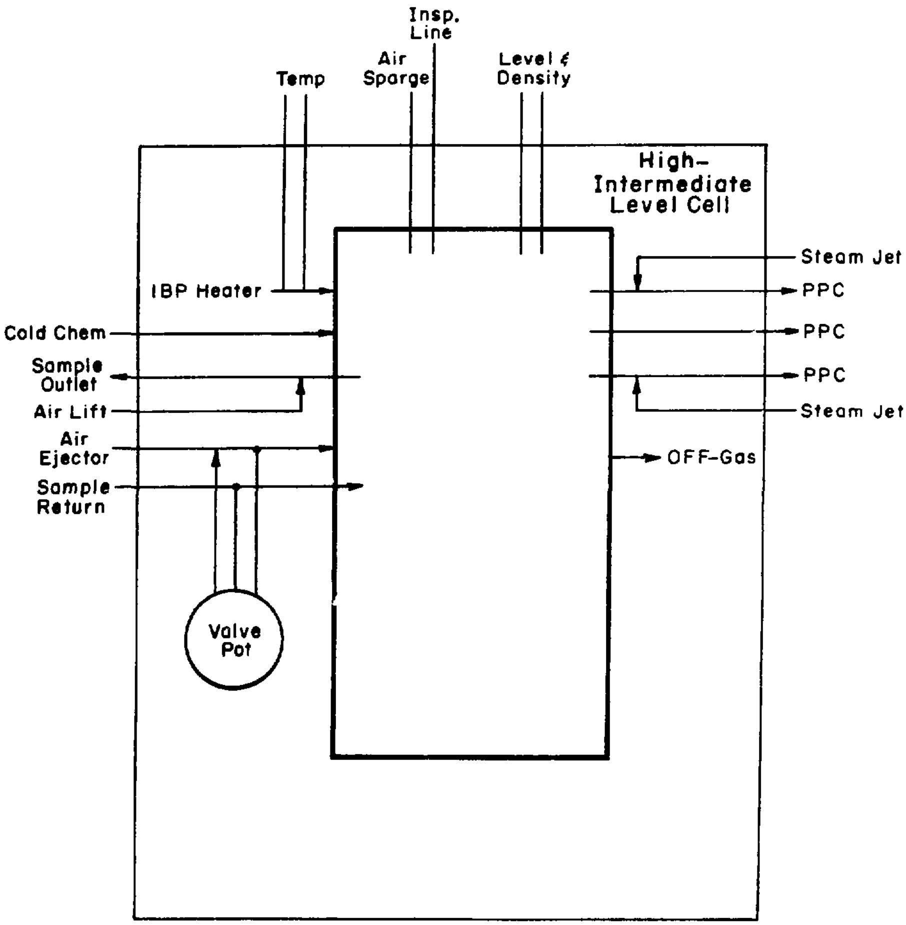

Fig. 5. Schematic of 1BP surge tank.

TABLE VIII

SENSORS FOR THE 1BP SURGE TANK

Lines	No. of Lines	Sensors
Inputs	1	Flow, liquid-in-line or radiation monitors
Outputs	3	None
Air sparge	1	Air flow monitor
Off-gas	1	None
Inspection	1	Air flow monitor
Cold chemical	1	Air flow monitor
Sample System	3	Circulation monitor and air flow monitors
Level and density	2	Pressure monitor

Total number of sensors = 9

g. Verification of Materials Balance. On the basis of his verifications and independent analyses, the inspector may draw his own materials balance and compare it with that reported by the operator. For near-real-time accountability, the inspector will need techniques for evaluating his data and comparing it with the operator's data to detect diversion or falsification. These techniques are described in Sec. V.

E. Safeguards in MBA 4

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

(1) KMP 8 - plutonium product sample tank; transfers of plutonium-nitrate product solution to MBA 4 from MBA 2.

(2) KMP 9 - plutonium product recycle tank; recycle of off-specification plutonium- nitrate product from MBA 4 to MBA 2.

(3) KMP 12 - receipt tanks; transfer of plutonium-nitrate product from MBA 4 to the conversion process area.

The inventory KMPs are KMP C1 to KMP C3, the interim plutonium-nitrate product storage tanks each with a capacity of ∿400 L; KMP C4, the 100-L measuring tank; and KMPs C5 to C52, the 48 ∿800-L product storage tanks.

1. Operator's Measurement and Accounting System. The operator's conventional measurement and accounting system will rely on input measurements through KMP 8, output measurements through KMPs 9 and 12, and periodic inventories of the storage tanks. Measurement methods for KMP 12 are expected to be similar to those described previously for KMPs 8 and 9.

An inventory of MBA 4 involves volume and density measurements at each inventory KMP (C1 to C52) and laboratory analysis of samples to determine plutonium concentration. Volume and density are determined in each tank with dip-tube bubbler systems. In-line density measurements are compared with measurements made in the laboratory using a digital densimeter. Concentration measurements are made in the laboratory by controlled-potential coulometry or an amperometric titration. X-ray fluorescence[53-56] and x-ray K-edge densitometry[58,64,65] are under consideration for on-line measurement of the plutonium concentration.

In-process inventory measurements are complicated by loss of liquid through evaporation and radiolytic decomposition. The alpha radiation from plutonium causes decomposition of water, generating hydrogen gas. Because hydrogen forms flammable mixtures when its concentration in air exceeds 4% by volume, the storage tanks are flushed with a continuous stream of air to dilute the hydrogen to an acceptable level. Water and some nitric acid evaporate into the stream of air. Studies of evaporation and radiolysis losses[73,74] estimated a total mass loss of 478 g/day for an 800-L tank. Of this loss, 473 g/day was water, and the balance was nitric acid. Thus, periodically it may be necessary for the operator to add dilute nitric acid to the tank to replace the lost liquid. In relating current volume and concentration measurements with previous measurements, one must account for the loss of liquid and any additions that may have been made.

2. Safeguards Concerns for MBA 4. There are two primary safeguards concerns for MBA 4. The first concern is diversion concealed by measurement uncertainties. Large quantities of plutonium may be present in this MBA. If all 3 interim storage tanks

and all 48 product storage tanks are filled with solution having a plutonium concentration of 250 g/L, MBA 4 could contain as much as 9900 kg of plutonium. In normal plant operation, the product storage tanks will contain 160 kg of plutonium per tank rather than the 200 kg used in this study. Material from some product storage tanks will be transferred to the conversion process, and at least one interim storage tank will be empty, awaiting transfer of solution from the plutonium product sample tank through KMP 8.

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

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

3. Verification Activities in MBA 4. Safeguards concerns for MBA 4 can be addressed through (1) verification of the conventional accounting measurements and containment/surveillance to ensure that all transfers pass through the appropriate measurement points or (2) providing improved materials accounting in MBA 4. The first approach is similar to that used in MBA 1.

a. Verification Activities for Conventional Accounting. Verification activities at KMP 8, the plutonium product sample tank, and KMP 9, the plutonium product recycle tank, were discussed in Sec. IV.D.3. Verification activities at KMP 12, the receipt tank in the plutonium conversion process area, will be similar to those described for KMP 9.

The inspector should verify the operator's volume and density measurements at the inventory KMPs. The inspector could verify the calibration and the operator's readings if he has independent readout and calibrating devices that are connected to the operator's pressure transducers. The inspector may request duplicate samples for the verification of plutonium concentration by x-ray densitometry,[58,64,65] x-ray fluorescence,[53-56] or gamma-ray spectrometry.[70,71] Transfers between tanks may have to be monitored to ensure that material is inventoried only once.

b. Surveillance of Containment Boundary Penetrations in MBA 4. Surveillance of containment boundary penetrations may be applied to MBA 4 as shown in Fig. 6. Surveillance serves the dual purpose of preventing undetected bypass of the recycle measurement at KMP 9 and providing for the detection of unreported inventory changes in MBA 4. The containment boundary encloses the plutonium-nitrate storage cells, the product storage operating galleries, and a portion of the plutonium product cell. The 116 identified penetrations of the containment boundary are listed in Table IX with examples of instruments that could monitor the penetrations. Sensor requirements are summarized in Table X ; the potential effectiveness of the surveillance systems is evaluated in Sec. V.B.

c. Improved Materials Accounting. In-process inventory measurements may be improved by on-line measurement of the plutonium concentration. X-ray fluorescence[53-56] or x-ray densitometry[58,64,65] are suitable techniques. The plutonium-nitrate

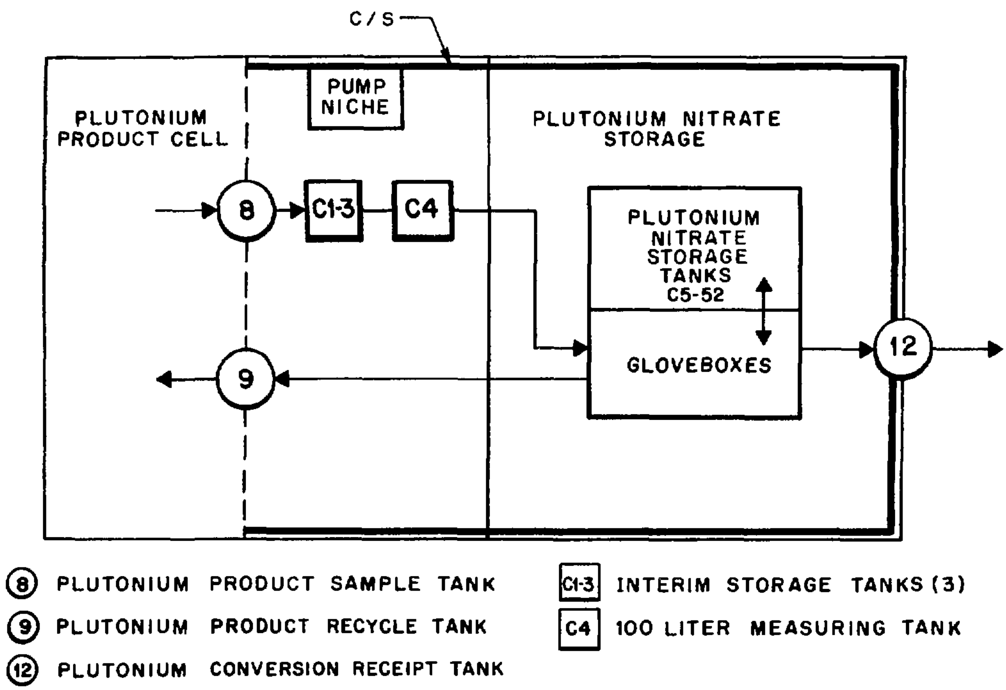

Fig. 6. Surveillance of MBA 4 containment boundary penetrations.

TABLE IX

PENETRATIONS OF MBA 4 CONTAINMENT

Penetrations	Category I Penetrations	Total No. of Penetrations[a]	Surveillance Measures[b]
Airlift air supply lines	1	2	LIL
Air/nitrogen purges	0	5	LIL
Air-sparge lines	5	5	LIL
Cold-chemical lines	0	2	PRM
Cooling water lines	0	6	PRM
Doors	2	3	1S, 2PP, 1EP
Hatches	0	2	S
Instrument lines	17	51	LIL
K-plugs	0	6	S
Off-gas lines	0	6	LIL
Rabbit ports	2	2	SC
Sample lines	14	14	SMSII
Spares	0	6	S
Steam lines	1	5	PRM
Ventilation lines	1	2	LIL
TOTAL	43	117	

[a]Category I plus Category II.

[b]EP = equipment portal
LIL = liquid-in-line sensor
PP = personnel portal
PRM = pipe radiation monitor
RM = radiation monitor
S = seal
SC = sample counter
SMSII = sample-monitoring system.

TABLE X

SUMMARY OF SENSORS IN MBA 4

Sensor	Sensors for Category I Penetrations	Total No. of Sensors[a]
Equipment portals	1	1
Liquid-in-line sensors	24	71
Personnel portals	2	2
Pipe radiation monitors	1	13
Sample counters	2	2
Sample-monitoring system II	1	1
Seals	0	15
TOTAL	31	105

[a]Category I plus Category II.

solution would be circulated continuously through the sample cell during the measurement to reduce sampling errors. The instrumentation would belong to the operator, but the inspector should verify all measurements. For timeliness and improved sensitivity, volume and on-line concentration measurements should be performed as frequently as possible.

An alternative approach involves long-term monitoring of liquid level, density, and temperature in the plutonium-nitrate storage tanks. Sequential analysis of these data using decision analysis techniques and the predicted losses from evaporation and radiolysis could improve the sensitivity to diversion in MBA 4.

The amount of plutonium in MBA 4 is based on design requirements to store the plutonium-nitrate product before transferring it to a separate conversion facility. With the change in US regulations that ban the shipping of plutonium-nitrate solutions and therefore require a collocated conversion facility, it is questionable if storage for >1 MT of plutonium will be required for US facilities. This reduction in storage capacity would improve both materials accounting and containment/surveillance effectiveness.

V. EVALUATION

Inspector safeguards activities described in Sec. IV are designed to verify that materials accounting data provided by the operator are complete and have not been falsified and that materials flows through the containment occur only at KMPs and are measured properly. Section V.A evaluates the inspector's sensitivity to detect diverted material that is hidden by measurement uncertainties and/or by the operator's falsification of his reported measurements. Section V.B evaluates the containment/surveillance system's detection sensitivity for material diverted through containment penetrations. Although the combined assurance provided by all inspector activities is not quantified in this report, Sec. V.C discusses the functional relationships among the elements comprising the combined assurance.

A. Quantifying the Effectiveness of Materials Accounting

1. Introduction. International safeguards for a nuclear facility require an inspector's independent verification of the operator's accounting data to deter the diversion of nuclear material from the facility or to detect a diversion at an early time.[9] Such verification activities include a combination of independent measurements by the inspector and verified operator measurements. As stated in Ref. 9, paragraph 30, "...the technical conclusion of the Agency's verification activities shall be a statement, in respect of each materials balance area, of the amount of material unaccounted for over a specific period, giving the limits of the accuracy of the amount stated."

Performance measures for nuclear materials accounting systems embody the concepts of loss-detection sensitivity and loss-detection time. Because of the statistical nature of materials accounting, loss-detection sensitivity can be described as the probability of detecting some amount of loss while accepting some probability of a false alarm. Loss-detection time is the time required by the accounting system to reach some specified level of loss-detection sensitivity. Note that the method of loss is not specified; whether the loss occurs in an abrupt or protracted fashion, the total amount of loss is the measure of performance. Note also that loss-detection time as defined here only refers to the internal response time of the accounting system.

Performance criteria for materials accounting systems result from external judgments concerning acceptable, or at least desirable, performance goals. Criteria are established for, or are directly relatable to, four performance measures: total amount of loss, loss-detection time, loss-detection probability, and false-alarm probability (or level of significance). For any materials accounting system, the four performance measures are not independent but are related by a continuous function that depends on the uncertainties of the materials measurements and on the particular loss method and statistical test applied to the accounting data.

Specific criteria suggested by the IAEA[11,19] are a 0.95 probability of detecting the loss of 8 kg of plutonium over a specified time period with a 0.05 false-alarm probability. The significant quantity of 8 kg was selected as being related to that quantity of plutonium required for a single nuclear explosive device. The time period for detection is the conversion time, defined as the time required to convert nuclear material to weapon form. For plutonium in spent fuel (MBA 1), this time is 1-3 months, and for plutonium in the nitrate form (MBA 2 and MBA 4) the time is 7-10 days.

Because the inspector may have limited resources for making his own measurements, verifying the operator's measurements, and analyzing these measurements, techniques have been developed by the IAEA to improve the inspector's efficiency. These techniques include inspection sampling plans and statistical methods of data analysis. Principles for selecting an inspection plan are discussed in Sec. V.A.2, and statistical methods are discussed in Sec. V.A.3.

2. Planning Inspections. An inspector's strategy for collecting materials accounting data includes specifying those quantities that should be measured and selecting a measurement method. This strategy will depend in part on the material being safeguarded, its form, and whether the inspector must detect a large loss from a few units (attributes defect) or a slight bias in the total inventory (variables defect).[11]

For those MBAs containing many units, the inspector could guard against large defects by selecting a random sample and using an attributes check such as verification of a serial number on a fuel assembly. Attributes checks verify the continued presence of a unit having appropriate gross characteristics without measuring the amount of material precisely. This is the current IAEA practice for fuel-assembly accounting in storage pools.

If the inspector wants to detect moderate size removals of material, then a variables-in-attributes mode inspection is appropriate. This usually involves a randomly selected group of items using a more sensitive measurement method such as a portable NDA instrument. Introduction of such methods is currently the chief goal of upgrading IAEA inspections.

If the inspector wants to detect materials losses that are sufficiently small to be hidden by measurement uncertainties, a variables inspection is required. The units sampled in a variables inspection should include all those containing a significant amount of material, and the measurement method (such as chemical analysis) should be sensitive to materials loss. Unlike the other inspection modes, variables inspection involves a collective analysis of the measurements to detect a significant shift in the total inventory.

An inspection plan is effective when it allows the inspector to meet performance criteria while reducing the number of quantities measured. Some general relationships between sample sizes for the three inspection modes are given below.

(1) If N_a is the attributes sample size and N_{V1} is the sample size for a variables-in-attributes inspection on the same quantities, typically $N_a \leq N_{V1}$ for the same detection probability.

(2) The sample size N_{V2} for variables inspection may be larger or smaller than N_a or N_{V1}.

(3) N_{V2} may become unacceptably large when measurement errors limit detection sensitivity.

In general, attributes inspection is most effective in areas, such as MBA 1, that contain large numbers of items, whereas variables inspection is most effective in areas containing bulk quantities, such as in MBA 2 where a materials balance is drawn.

3. Inspector's Sufficient Statistics. Because the operator can hide diversion through falsification of his reported data or in the measurement uncertainties, it is important that the inspector have a test statistic that prohibits both possibilities. A third possible diversion strategy--increasing the operator's measurement variances to hide measurement uncertainty--should be countered by the inspector's participation in the operator's measurement control program to verify the operator's stated measurement variances.

Consider a single balance period and an MBA with true initial and final inventories I_0 and I_1, and true input and output transfers T_0 and T_1. The operator measures these quantities, diverts some goal quantity of material, and then reports to the inspector the possibly falsified inventory and transfer measurements denoted by $\bar{I}_0$, $\bar{I}_1$, $\bar{T}_0$, and $\bar{T}_1$, where $\bar{I}_0$ and $\bar{I}_1$ are the operator's reported inventory measurements and $\bar{T}_0$ and $\bar{T}_1$ are the operator's reported transfer measurements. Note that for the reference process the initial and final inventory measurements ($\bar{I}_0$ and $\bar{I}_1$) will each be the sum of measurements made on several process vessels, and the input and output transfer measurements ($\bar{T}_0$ and $\bar{T}_1$) each will be the sum of many individual transfer measurements.

The inspector may make his own independent measurements; however, in some cases he verifies the operator's measurements with containment/surveillance devices that ensure the integrity of measurement instruments, or he uses inspector presence to observe measurement procedures. The inspector's measurements are denoted by $\tilde{I}_0$ and $\tilde{I}_1$ (inventory measurements) and $\tilde{T}_0$ and $\tilde{T}_1$ (transfer measurements). Again these inventory and transfer measurements are sums of individual measurements.

As a part of this verification procedure, the inspector should verify the operator's measurement control program to validate the operator's stated measurement uncertainties and to prevent their inflation for the purpose of hiding diversion. The variance of an inspector's measurement depends on many factors not yet determined, such as the type of measurement equipment and the facilities for recalibrating instruments, including availability of standards. The inspector's measurement standard deviations are treated parametrically, varying from equality with the corresponding operator's measurement standard deviations up to a factor of two larger.

To protect against both operator's data falsification and diversion hidden in measurement uncertainty, we introduce the inspector's sufficient statistic (ISS). The ISS takes different forms, depending on the amount of information the inspector wants to extract from the aggregate of the inspector's and operator's measurements. The statistic ISS_0 can be written as

$$ISS_0 = \frac{\max\,[0,\ \bar{I}_0 - \tilde{I}_0](\bar{I}_0 - \tilde{I}_0)}{2[\bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0)]} + \frac{\max\,[0,\ \bar{I}_1 - \tilde{I}_1](\bar{I}_1 - \tilde{I}_1)}{2[\bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1)]}$$

$$+ \frac{\max\,[0,\ \bar{T}_0 - \tilde{T}_0](\bar{T}_0 - \tilde{T}_0)}{2[\bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0)]} + \frac{\max\,[0,\ \bar{T}_1 - \tilde{T}_1](\bar{T}_1 - \tilde{T}_1)}{2[\bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1)]}$$

$$+ \frac{\max\,[0, M_p]M_p}{2\sigma_p^2} \ .$$

M_p is a weighted sum of operator's and inspector's materials balances given by

$$M_p = \frac{\tilde{\sigma}_I^2(0)\bar{I}(0) + \bar{\sigma}_I^2(0)\tilde{I}(0)}{\bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0)} - \frac{\tilde{\sigma}_I^2(1)\bar{I}(1) + \bar{\sigma}_I^2(1)\tilde{I}(1)}{\bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1)}$$

$$+ \frac{\tilde{\sigma}_T^2(0)\bar{T}(0) + \bar{\sigma}_T^2(0)\tilde{T}(0)}{\bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0)} - \frac{\tilde{\sigma}_T^2(1)\bar{T}(1) + \bar{\sigma}_T^2(1)\tilde{T}(1)}{\bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1)} \quad ,$$

and the variance of M_p is

$$\sigma_p^2 = \frac{\bar{\sigma}_I^2(0)\tilde{\sigma}_I^2(0)}{\bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0)} + \frac{\bar{\sigma}_I^2(1)\tilde{\sigma}_I^2(1)}{\bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1)}$$

$$+ \frac{\bar{\sigma}_T^2(0)\tilde{\sigma}_T^2(0)}{\bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0)} + \frac{\bar{\sigma}_T^2(1)\tilde{\sigma}_T^2(1)}{\bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1)} \quad ,$$

where $\sigma_I^2(i)$ and $\sigma_I^2(i)$ are the operator's and inspector's inventory measurement variances, and $\sigma_T^2(i)$ and $\sigma_T^2(i)$ are the operator's and inspector's transfer measurement variances, with $i = 0, 1$. The first four pieces of this statistic are sensitive to falsification, and the fifth piece is sensitive to missing material. This form of the statistic allows the inspector to test for falsification in individual components of the operator's data as well as for missing material.

If the inspector is not interested in testing for falsification in individual components but only in the total falsification, he employs the static ISS_1, which is written as

$$ISS_1 = \frac{\max\,[0, F]F}{2\sigma_F^2} + \frac{\max\,[0, M_p]M_p}{2\sigma_p^2} \quad ,$$

where F represents total falsification, that is,

$$F = (\bar{I}_0 - \tilde{I}_0) - (\bar{I}_1 - \tilde{I}_1) + (\bar{T}_0 - \tilde{T}_0) - (\bar{T}_1 - \tilde{T}_1) \quad ,$$

and σ_F^2 is the variance of F, which is given by

$$\sigma_F^2 = \bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0) + \bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1) + \bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0) + \bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1) \quad .$$

If the inspector is not concerned with falsification and wishes to be independent of it, he should use ISS_2, which is written as

$$ISS_2 = \frac{\max\,[0, M_v] M_v}{2\sigma_v^2} \quad ,$$

where M_v is the inspector's materials balance, which is

$$M_v = \tilde{I}(0) - \tilde{I}(1) + \tilde{T}(0) - \tilde{T}(1) \quad ,$$

and the variance of M_v is

$$\sigma_v^2 = \tilde{\sigma}_I^2(0) + \tilde{\sigma}_I^2(1) + \tilde{\sigma}_T^2(0) + \tilde{\sigma}_T^2(1) \quad .$$

Although M_p included the operator's measurements, which may not have been verified, and the inspector's measurements, M_v includes only those measurements that the inspector knows to be valid.

These statistics can be applied to test the hypothesis

H_0 :falsification = 0 <u>and</u> diversion = 0

against the alternative hypotheses

H_1 :falsification > 0 <u>and/or</u> diversion > 0.

The test is implemented by calculating the value of the relevant statistic ISS_0, ISS_1, or ISS_2 and applying the decision rule

accept H_0 if $ISS_i \leq \lambda_i$;

accept H_1 if $ISS_i > \lambda_i$,

where the decision threshold λ_i, i = 0,1,2, is chosen to achieve some false-alarm probability. For a false-alarm probability of 0.05, the values of λ_i are 1.35, 4.23, and 7.48, respectively. A formal derivation of these statistics and their use in hypothesis testing may be found in Ref. 3, Appendix H ; Ref. 17 ; and in Appendix B of this report.

These statistics are sensitive to the total amount of material diverted, but are independent of the particular diversion path through which the material is diverted. The statistics do, however, depend on how the operator falsifies his reported data. For this report, we assume that the operator follows his optimal strategy, which is to set the total falsification equal to the amount diverted.[17]

The test procedure described here does not maximize the power of detection against all levels of diversion ; however, this procedure has the greatest potential among those that we evaluated. Investigation to improve the application of the ISS to materials accounting continues. In presenting the sensitivity of these statistics to anomalies in the measurement data, we have considered balance periods ranging from 7 days to 360 days. In effect this is a sequence of fixed-length tests, and the detection probability for these tests provides a lower boundary for results in a sequential test. By considering a range of balance periods, the results can be presented as the probability of detecting some amount of diverted material over a given time period and with a given false-alarm probability. The relationship between these quantities can be expressed in a performance surface comprising a three-dimensional plot of detection probability as a function of diverted amount and detection time for a fixed false-alarm probability.

Another approach to testing the operator's reported measurements for falsification and/or diversion is to employ the statistics MUF and D.[27] The statistic MUF is a materials balance based on the operator's reported data,

$$MUF = \bar{I}(0) - \bar{I}(1) + \bar{T}(0) - \bar{T}(1) \quad ,$$

and the statistic D is the inspector's estimate of falsification in the operator's data,

$$D = \frac{N}{n}\{[I(\bar{0}) - \tilde{I}(0)] - [\bar{I}(1) - \tilde{I}(1)] + [\bar{T}(0) - \tilde{T}(0)]$$

$$- [\bar{T}(1) - \tilde{T}(1)]\} \quad ,$$

where N is the total number of the operator's measurements and n is the number sampled by the inspector.

The D statistic can be used to test for falsification. When the operator's data are found to be unfalsified, the operator's materials balance MUF is used to test for missing material. The statistic ISS_1 is better for this purpose because the piece sensitive to falsification and the piece sensitive to diversion are statistically independent; whereas MUF and D are not independent.

In an alternative testing procedure MUF and D could be combined as MUF - D, which is the operator's materials balance corrected by the inspector's estimate of data falsification. This statistic tests only for missing material. In the case of 100% sampling, MUF - D is identical to ISS_2, which is just the inspector's materials balance.

<u>4. Sampling in the Reference Facility</u>. In MBA 1 of the reference facility, item accounting of fuel assemblies is the form of materials accounting proposed by the IAEA. With the exception of the chop/leach area where plutonium enters in item form and is transferred out in bulk form through the accountability tank, all of the fuel-assembly inventory for MBA 1 is in item form in the storage pool. Because of the potentially large

number of assemblies in the storage pool, during routine inspections the inspector must rely on some form of sampling using an attributes-type measurement, such as the Cerenkov glow observation, to establish assembly integrity.

In MBA 2 the proposed accounting procedure is to draw a materials balance. This implies that the inspector should verify significant materials inventories in the tanks and vessels of MBA 2 and significant materials transfers into and out of this area. Because there is only one opportunity to detect falsification in an operator's reported transfer measurement, the inspector should verify all the transfers at KMPs. However, for inventory measurements, falsification in one balance period must be continued over all successive periods, or a loss will appear in the materials balance. This implies that the inspector need not verify all inventory measurements using an accurate variables-mode measurement in each balance period. Instead, an attributes inspection plan may be sufficient if a variables-mode measurement is intermittently made on each inventory quantity.

The inspector need not sample from all process measurements for every routine inventory verification; tanks and vessels containing a significant quantity of plutonium are of most interest. Table XI lists all inventory KMPs and some additional strategic points.

Considerations in developing an inspection plan for MBA 4 are similar to those encountered in MBA 2. In particular, each of the 48 slab tanks in MBA 4 may contain up to 200 kg of plutonium; therefore, detecting removal of a goal quantity of plutonium requires that the inspector apply an inspection plan similar to the plan for MBA 2.

5. Accounting Strategies. The inspector's analysis of his own verified data and the operator's reported data should consider the two potential operator methods for hiding diversion through either data falsification or measurement uncertainties. The ISS developed in this report combines both inspector's and operator's data in testing for either possibility. This statistic can be applied to accounting data from each of the MBAs independently.

The current IAEA method for safeguarding irradiated fuel applies item accounting to individual fuel assemblies. For MBA 1 this procedure consists of verifying the identity and integrity of fuel assemblies at KMPs located in the unloading pool where irradiated fuel is received, the storage pool, and the transfer tunnel where irradiated fuel is moved to the chop/leach area. Inspection planning in this area must consider the large number of items in the inventory and the small number of items that must be diverted to attain 8 kg

TABLE XI

PLUTONIUM BULK INVENTORY IN MBAs 2 AND 4

Tank	Volume (L)	Plutonium Concentration (g/L)	Total Plutonium (kg)
Accountability tank	6 700	2.97	19.9
Feed adjustment tank(2)	7 200	2.76	19.9
HWW sample tank	2 358	0.141	0.33
Centrifuge	80	2.76	
HA feed tank	13 000	2.76	35.9
1BP surge tank	1 500	4.94	7.4
2A column	--	--	4.59
2B column	--	--	2.80
3A column	--	--	5.42
3B column	--	--	4.80
3PS wash column	--	--	1.17
3P concentrator	60	250.0	15.0
Pu catch tank	65.7	250.0	16.4
Pu product sample tank	197	250.0	49.2
Pu interim storage tanks (3)	394 (each)	250.0	98.5 (each)
Slab tanks (48)	800 (each)	250.0	200.0 (each)

of plutonium. This suggests an attributes sampling plan in which only selected fuel assemblies are verified using an attributes or variables-in-attributes measurement. Instrumentation for verifying the identity and integrity of fuel assemblies is described in Sec. IV and Appendix A.

Although it is not current IAEA policy to perform materials accounting in MBA 1 by using variables type measurements to close a materials balance, such a procedure may be desirable at least in the chop/leach area where item accounting is not possible. Although variables measurements using NDA instruments may not be feasible in the storage pool because of the inaccessibility and large numbers of fuel assemblies, such measurements could be made when assemblies are transferred into the chop/leach area. A materials balance for the chop/leach area could be formed by making NDA measurements of the plutonium in each fuel assembly entering the transfer tunnel, which constitutes the input transfer measurement for this area, and by using plutonium measurements in the accountability tank as the output transfer measurement. For materials balance intervals of about 6 days, the dissolvers will be empty at the beginning and end of each balance period so that no inventory will exist, and the materials balance is reduced to the difference between input and output transfers.

Using these measurements and surveillance methods for assuring their integrity, the ISS can be applied to test accounting data for falsification and/or missing material. The uncertainty in the testing procedure will be dominated by the NDA measurement error with a relative standard deviation of $\sim$5%. Materials balances are calculated for pressurized water reactor (PWR) fuel assemblies containing $\sim$4.5 kg of plutonium.

A materials balance for MBA 2 will be formed from measurements made at KMPs supplemented with additional inventory measurements made at strategic points. As discussed in Sec. V.A.2, it is necessary to verify all transfer measurements across the MBA boundary, which for MBA 2 are the KMPs at the accountability tank and the plutonium sample tank. The inventory in MBA 2 is based upon the KMP measurements at the feed adjustment tank and 1BP surge tank. Additional inventory measurements or estimates will be required at the HA feed tank, 2A, 2B, 3A, 3B, and 3PS wash columns, concentrator, and plutonium catch tank. The feasibility of these measurements has been demonstrated in a series of experiments at the AGNS facility.[75-78] For verification, the inspector need not use high-quality measurements at all points, but instead he may use sampling combined with an attributes measurement. This relaxation of requirements for inventory measurement points is based on the operator's difficulties in falsifying inventory measurements as discussed in Sec. V.A.2.

Input transfers are made from the accountability tank at 2.5/day; and output transfers from the plutonium product sample tank at 1/day. The total inventory of plutonium in MBA 2 is $\sim$100 kg; each input transfer from the accountability tank contains $\sim$20 kg of plutonium, and each output transfer from the sample tank contains $\sim$50 kg of plutonium.

Materials accounting in the plutonium-nitrate storage area, MBA 4, may be applied by closing a materials balance in which the inventory consists of plutonium in the forty-eight 800-L slab tanks and the three interim storage tanks. Input transfers are the contents of the plutonium product sample tank, and output transfers are the contents of one slab tank. Output transfers from MBA 4 are based upon a single 200-kg plutonium transfer from one slab tank at 8-day intervals. All of those inventory and transfer points are KMPs and will be verified on the same basis as the measurements in MBA 2.

6. Measurement Uncertainties. Evaluating the sensitivity of the ISS to missing material requires an assignment of random and systematic error variances to each of the measurements that comprise the inspector's and operator's materials balances. Because these balances may be closed in near-real-time, the KMPs identified in Sec. IV should be supplemented with measurements at other points in the process. For this purpose, assume that measurements (either direct or indirect) are available for the chop/leach area at the transfer tunnel; for MBA 2 at the accountability tank, feed adjust tanks, IBP surge tank, pulsed columns (2A, 2B, 3A, 3B, 3PS wash), concentrator, plutonium catch tank, and plutonium product sample tank; and for MBA 4 at the interim storage and slab tanks. The measurement at the transfer tunnel is by NDA. Table XII summarizes the relative standard deviations (RSDs) for the random and systematic errors of those measurements that are important in the materials balance equation.

The uncertainty in a materials balance for the chop/leach area is dominated by NDA errors in the input transfer measurement. These errors are characterized by RSDs of ∿4% random and ∿3% systematic for PWR assemblies, and ∿6% random and ∿5% systematic for boiling water reactor (BWR) assemblies.[46]

The amount of plutonium in the tanks and other vessels in MBAs 2 and 4 of the reference process is measured by the product of volume and concentration. Error models for these measurements are assumed to have the multiplicative forms

$$\bar{V} = V(1 + \epsilon_V + \eta_V) \quad \text{and} \quad \bar{C} = C(1 + \epsilon_C + \eta_C) \quad ,$$

where V and C are the true values of the volume and concentration, $\bar{V}$ and $\bar{C}$ are the measured values, ϵ_V and ϵ_C are the random measurement errors, and η_V and η_C are systematic measurement errors. The plutonium measurement is the product of V and C, and the variance of the measurement is approximately

$$\sigma^2_{Pu} = \bar{V}^2\bar{C}^2(\sigma^2_{\epsilon_C} + \sigma^2_{\epsilon_V} + \sigma^2_{\eta_C} + \sigma^2_{\eta_V}) \quad .$$

TABLE XII

PRECISION AND CALIBRATION ERRORS FOR ASSUMED MEASUREMENT POINTS

Measurement Point	Measurement Type	Precision (% 1σ)	Calibration Error (% 1σ)
Transfer tunnel	NDA	4.0	3.0
Accountability tank[a]	Volume	0.3	0.1
	Concentration	1.0	0.3
Feed adjust tank[a]	Volume	0.3	--[b]
	Concentration	1.0	--[b]
HA feed tank	Volume	0.3	--[b]
	Concentration	1.0	--[b]
1BP surge tank[a]	Volume	0.3	--[b]
	Concentration	1.0	--[b]
2A, 2B, 3A, 3B, 3PS wash columns		10.0	--[b]
Concentrator	Volume	3.0	--[b]
	Concentation	3.0	--[b]
Pu catch tank	Volume	3.0	--[b]
	Concentration	3.0	--[b]
Pu sample tank[a]	Volume	0.3	0.1
	Concentration	0.2	0.1
Storage and slab tanks	Volume	0.3	0.1
	Concentration	0.2	0.1

[a]KMP.

[b]Approximately constant amounts of material; systematic errors tend to cancel.

In modeling the effect of recalibration on measurement uncertainty, the volume measurement systematic error η_V is decomposed as $\eta_V = \eta + \theta$, where η represents the error that is affected by recalibrating the pressure measuring system, and θ represents the error that is unaffected by such recalibration (for example, the relationship between volume of liquid in the tank and the observed liquid level). The error term θ is assumed to have a 0.05% RSD. It is assumed that the pressure measuring system for concentration and volume in the accountability tank and in the sample tank are recalibrated once per shift. This level of recalibration activity is not unreasonable, given, for example, an on-line recalibration system such as that installed in the BNFP.[51]

7. Diversion Sensitivity of the ISS. The sensitivity of the ISS to falsification in the operator's reported measurements and/or diversion is summarized in Tables XIII-XV. The sensitivity for MBA 4 was calculated for maximum design capacity (9.9 MT of plutonium) and for reduced capacity (3 and 1 MT), assuming a collocated conversion facility with a reduced need for plutonium-nitrate storage capacity. For these tables, the inspector's materials balance uncertainty is assumed to be equal to the operator's uncertainty. Results for the ISS_2 statistic, summarized in Table XV, establish that the IAEA goal of detecting 8 kg of missing material within 1-3 wk with a 0.95 probability and an 0.05 false-alarm probability can be attained in MBA 2. Further, the 8-kg quantity is detected within 7 days with probabilities 0.64 and 0.26 in the chop/leach and 9.9 MT capacity nitrate storage areas, respectively. Although these probabilities are not as large as the corresponding detection probability in MBA 2, these results illustrate that dynamic

TABLE XIII

DETECTION PROBABILITY FOR ISS_0[a]
(Inspector SD equal to Operator SD)

	Balance Period (days)			
Balance Area	7	30	180	360
Chop/leach	0.51	0.19	0.09	0.08
MBA 2	0.92	0.71	0.19	0.16
MBA 4; 9.9 MT	0.20	0.19	0.15	0.10
MBA 4; 3 MT	0.69	0.59	0.19	0.11
MBA 4; 1 MT	0.97	0.80	0.20	0.12

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

TABLE XIV

DETECTION PROBABILITY FOR ISS_1[a]

(Inspector SD equal to Operator SD)

Balance Area	Balance Period (days)			
	7	30	180	360
Chop/leach	0.56	0.20	0.09	0.08
MBA 2	0.94	0.75	0.20	0.17
MBA 4; 9.9 MT	0.21	0.20	0.15	0.11
MBA 4; 3 MT	0.74	0.65	0.20	0.11
MBA 4; 1 MT	0.98	0.84	0.21	0.13

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

TABLE XV

DETECTION PROBABILITY FOR ISS_2[a]

(Inspector SD equal to Operator SD)

Balance Area	Balance Period (days)			
	7	30	180	360
Chop/leach	0.64	0.25	0.11	0.09
MBA 2	0.97	0.82	0.25	0.20
MBA 4; 9.9 MT	0.26	0.24	0.17	0.13
MBA 4; 3 MT	0.81	0.73	0.24	0.13
MBA 4; 1 MT	0.99	0.90	0.26	0.15

[a]Diversion of 8 kg of plutonium; 0.05 false-alarm probability one materials balance.

materials accounting can make a significant safeguards contribution even in those areas such as chop/leach where it has not traditionally been considered.

If the current 48 slab tanks of MBA 4, each containing 200 kg of plutonium, were reduced to <16 tanks, each containing 100 kg of plutonium, the IAEA goals for abrupt diversion could be met. If we assume storage capacity for 20 days of throughput is sufficient for a plant with a collocated conversion facility, 10 storage tanks, each with 100 kg of plutonium, would be adequate for MBA 4.

If ISS_2 is applied to the accounting data, falsification is ignored. In those instances where the inspector is interested in detecting missing material and/or falsification of the operator's reported measurements, the ISS_0 and ISS_1 statistics are applicable. The detection probability results for these statistics (Tables XIII and XIV) show that in testing for both falsification and diversion the inspector must accept a slightly lower probability of detection for the same level of diversion; however, in doing so he forces the divertor to falsify optimally to achieve the minimum detection probabilities shown. Detection sensitivities for ISS_1 are summarized in Figs. 7-11 for balance periods of 1 to 360 days.

Increasing the inspector's measurement uncertainties will, of course, reduce the detection sensitivities stated in Tables XIII-XV. For an inspector's materials balance RSD that is twice that of the operator's, Tables XVI-XVIII summarize the detection sensitivity. Under this restriction the IAEA goal for detecting abrupt diversion cannot be attained.

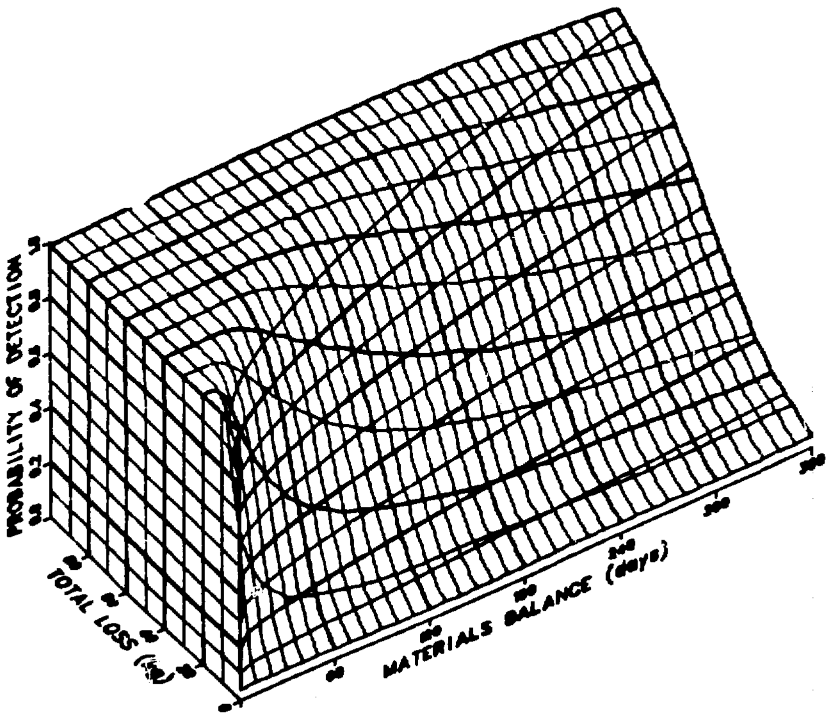

Fig. 7. Diversion sensitivity of ISS_1 in the chop/leach area.

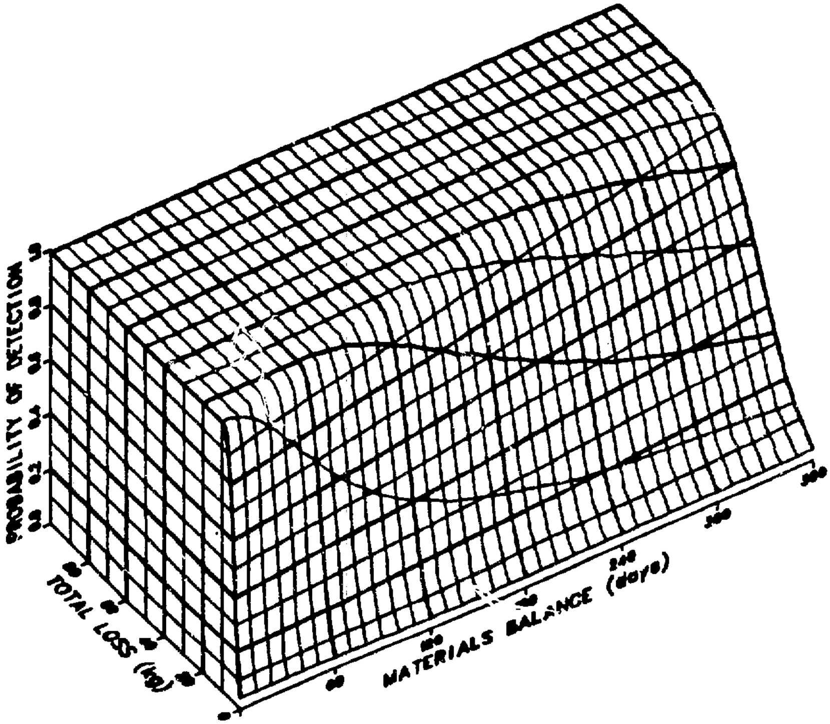

Fig. 8. Diversion sensitivity of ISS_I in MBA 2.

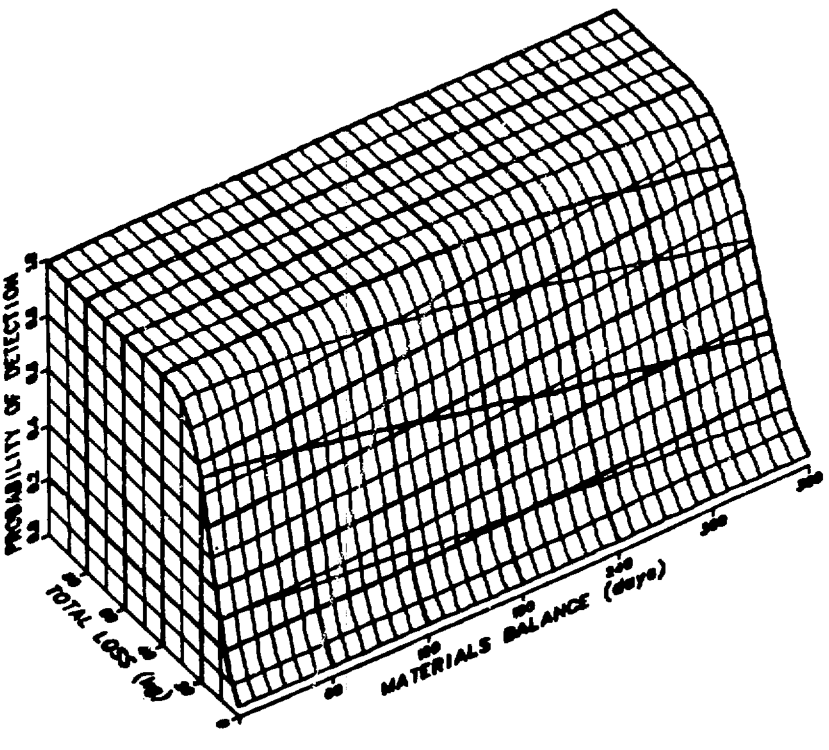

Fig. 9. Diversion sensitivity of ISS_I in MBA 4; 9.9 MT.

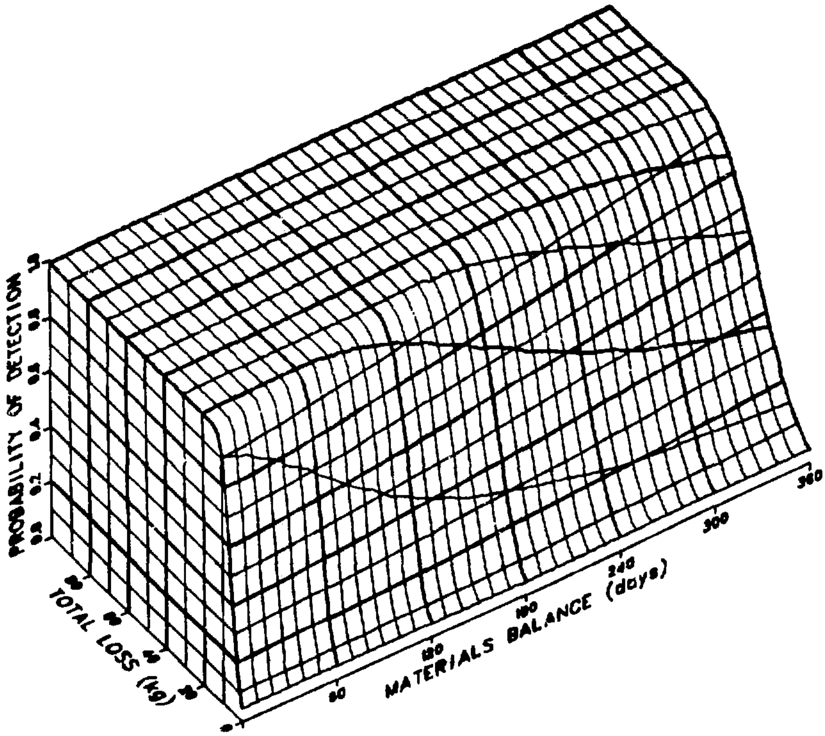

Fig. 10. Diversion sensitivity of ISS_1 in MBA 4; 3 MT.

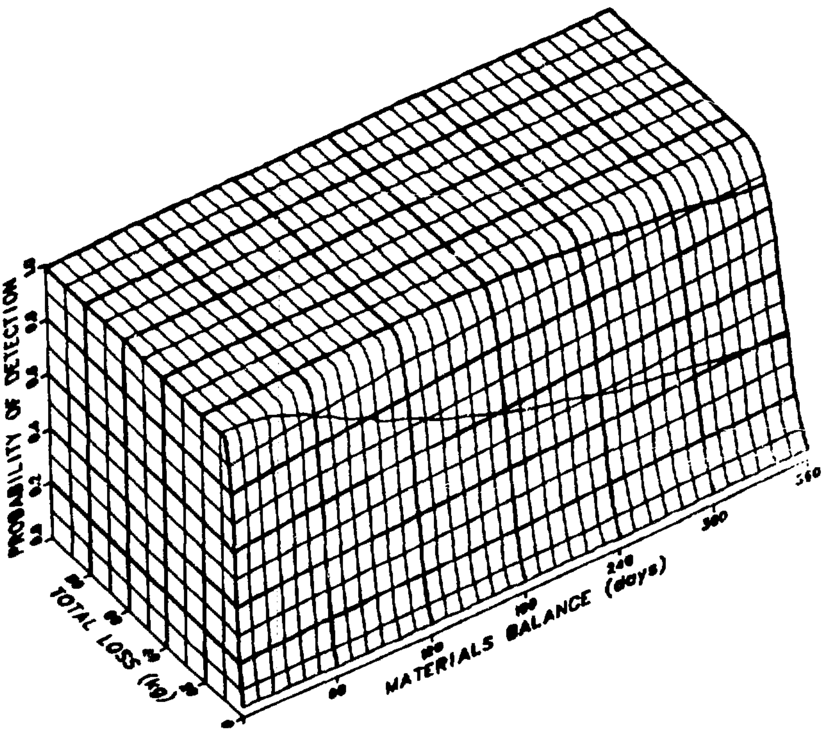

Fig. 11. Diversion sensitivity of ISS_1 in MBA 4; 1 MT.

TABLE XVI

DETECTION PROBABILITY FOR ISS_0[a]
(Inspector SD Equals 2x Operator SD)

Balance Area	Balance Period (days) 7	30	180	360
Chop/leach	0.20	0.10	0.08	0.07
MBA 2	0.42	0.27	0.10	0.08
MBA 4; 9.9 MT	0.10	0.09	0.08	0.06
MBA 4; 3 MT	0.26	0.22	0.10	0.07
MBA 4; 1 MT	0.51	0.32	0.10	0.07

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

TABLE XVII

DETECTION PROBABILITY FOR SS_1[a]
(Inspector SD Equals 2x Operator SD)

Balance Area	Balance Period (days) 7	30	180	360
Chop/leach	0.21	0.11	0.08	0.07
MBA 2	0.47	0.30	0.11	0.08
MBA 4; 9.9 MT	0.11	0.10	0.08	0.07
MBA 4; 3 MT	0.29	0.25	0.10	0.07
MBA 4; 1 MT	0.56	0.37	0.11	0.08

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

B. Quantifying the Effectiveness of Containment/Surveillance

1. Quantifying the Effectiveness of Boundary Penetration Surveillance. The performance of surveillance instrumentation systems designed to monitor containment boundary penetrations has been defined in terms of sensitivity and tendency to false alarm. Sensitivity describes the potential or predicted response of the system to an actual diversion. Systems sensitivity is defined by the amount of nuclear material

TABLE XVIII

DETECTION PROBABILITY FOR ISS_2[a]

(Inspector SD Equals 2x Operator SD)

Balance Area	Balance Period (days)			
	7	30	180	360
Chop/leach	0.26	0.13	0.10	0.08
MBA 2	0.55	0.35	0.14	0.09
MBA 4; 9.9 MT	0.13	0.12	0.10	0.08
MBA 4; 1 MT	0.64	0.44	0.13	0.09

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

potentially diverted and the time interval over which diversion occurs. The false-alarm probability is a measure of the tendency of the system to indicate material movement through an instrumented penetration when no such movement has occurred.

The potential sensitivity of these containment/surveillance systems is characterized by the probability P(d) that at least one indication of material being removed through an instrumented penetration occurs during the course of the removal, over a fixed time period T, of an amount of nuclear material d. During the time period T, one or more opportunities for removing material through a monitored penetration may occur. At each opportunity i the potential divertor may remove an amount m_i, and an alarm decision based on surveillance device performance is made. The sensor's sensitivity is characterized by the probability $p_i(m_i)$ that such a removal is detected. If all decisions are independent, then for a particular system of instrumented penetrations and time T characterized by N opportunities and a specific set of m_i, the systems sensitivity P(d) may be expressed as:

$$P(d) = 1 - \prod_{i=1}^{N} [1 - p_i(m_i)] \quad .$$

The value of P(d) depends upon allocation of the total amount of material diverted (d) over N opportunities because the functions p_i are not necessarily identical. Thus, P(d) is also a function of the N-vector $\underset{\sim}{m}$ and may be written $P(d,\underset{\sim}{m})$ to reflect this dependence. A conservative approach to systems evaluation has been taken in which the system sensitivity is characterized by $P(d,\underset{\sim}{m}^*)$, where $\underset{\sim}{m}^*$ represents the diversion strategy with which a potential divertor maximizes the probability of avoiding detection. Appendix C describes a method for determining $P(d,\underset{\sim}{m}^*)$ that employs a network representation of a system of instrumented penetrations and dynamic programming techniques for determining the optimum diversion strategy.

Two measures were developed to characterize the false-alarm tendency of a system. The first is the probability F that at least one false indication of potential diversion is generated by the system over a specified time period and is given by

$$F = 1 - \prod_{i=1}^{N} (1 - f_i) \quad ,$$

where f_i is the probability that the i^{th} decision generates a false positive indication of material movement. In addition, the expected number of false alarms (N_f) may easily be computed.

$$N_f = \sum_{i=1}^{N} (f_i) \quad .$$

This performance quantification model requires the specification of p(m) and f for each type of surveillance device. Ideally, values for these parameters would come from experiments; however, some of the surveillance devices are conceptual, and very little experimental information is available even for existing devices. To evaluate the systems proposed for the reference facility, performance parameter values were obtained by modeling six generic types of surveillance devices; these models and the resulting values are also described in Appendix C.

2. Systems Evaluation in the Reference Facility. Section IV describes conceptual system designs for monitoring containment boundary penetrations in MBAs 1 and 4. The systems were intended to provide timely indication of potential diversion from these areas. Two options were presented for each area: Option II (including Category I and II penetrations), all identified penetrations were assigned surveillance instruments, and in Option I (including only Category I penetrations), diversion through certain penetrations was judged incredible and therefore no monitors were required for those penetrations. For both options, $P(d,\tilde{m}^*)$ and the expected false-alarm rate N_f/T were determined for time span T of 10 days, 30 days, 180 days, and 360 days. In Figs. 12 and 13, for MBAs 1 and 4, respectively, $P(d,\tilde{m}^*)$ is plotted as a function of d, the total amount diverted. The results are summarized in Table XIX.

The sensitivity of the two system options in both the headend and the product storage MBA is identical. The identical results occur because additional penetrations monitored by the Option II systems are not used in the divertor's optimum strategies.

In MBA 1, the optimum diversion strategy is to remove material at low concentrations through pipes monitored by a radiation monitor. Even with the optimum strategy, $P(d,m^*)$ is >0.95 for diversion amounts >300 g. This sensitivity is independent of time for periods >10 days because at T = 10 days, the optimum strategy uses <2% of the available opportunities to divert past a pipe radiation monitor. Allowing a divertor more time only provides more opportunities that will not be used. Option I has an expected false-alarm rate of ~7/yr, whereas Option II has an expected false-alarm rate of ~14/yr.

In MBA 4, the optimum diversion strategy involves removing the sample material in routine samples and removing material through personnel and equipment portals. System sensitivities are time dependent because additional time allows the potential divertor to divide a given amount of material into smaller amounts for removal through the portal monitors, reducing the composite probability of detection. The Option I system would be expected to false alarm about 4 times/yr, whereas the Option II system would have an annual false-alarm rate of about 7.

These results suggest that fairly high sensitivities may be attainable with surveillance of containment boundary penetrations in both MBAs 1 and 4 for periods of 10 days or less. However, this sensitivity is achieved at the cost of 10 to 20 false alarms expected annually. For periods longer than 10 days, systems sensitivity decreases appreciably in MBA 4 but remains high in MBA 1. Protracted diversion over long time periods thus remains a concern in MBA 4. In practice, the achievement of these systems sensitivities would depend upon the successful development of sensors with the

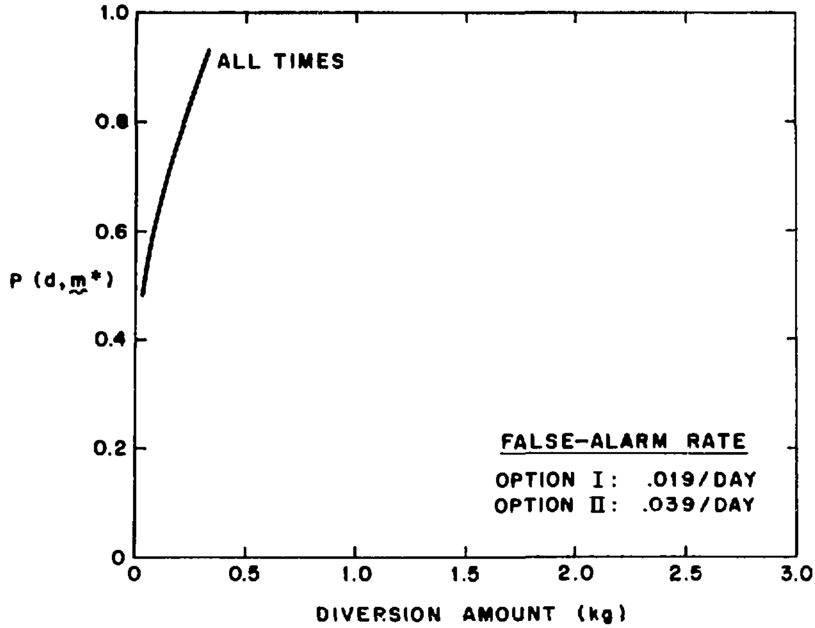

Fig. 12. MBA 1--system sensitivity.

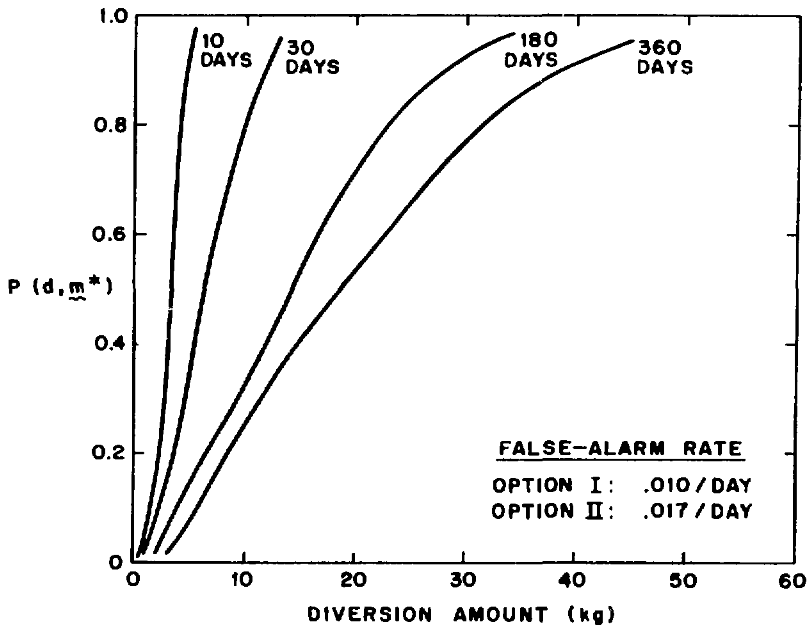

Fig. 13. MBA 4--system sensitivity.

TABLE XIX

SENSITIVITY OF PENETRATION-MONITORING SYSTEMS

	Detection Probability[a]			
	Balance Period (days)			
	10	30	180	360
MBA 1	>0.95	>0.95	>0.95	>0.95
MBA 4[b]	>0.95	0.82	0.26	0.19

[a]Probability of at least one alarm during the diversion of 8 kg of plutonium with an expected false-alarm rate of 0.019/day in MBA 1 and 0.010/day in MBA 4.

[b]Computed for MBA 4 configured to store 9.9 MT of plutonium.

performance characteristics described in Appendix C. These characteristics, although plausible, may in some cases incorrectly estimate the sensitivity of an actual device, and therefore, the system sensitivities. The results reflect the application of boundary penetration surveillance to a facility that was not designed for safeguards. A new facility in which safeguards planning was integral in the design might have containment/ surveillance systems with better sensitivity and/or a lower false-alarm rate.

C. Quantifying the Overall Assurance

The assurance provided by IAEA safeguards is necessarily founded on technical considerations, but it also incorporates more subjective factors. This section examines how the technical and subjective factors combine to provide an overall assurance. The following discussion is intended to provide a qualitative, heuristic approach to these relationships.

We define assurance in terms very similar to those for probability. That is, assurance has a numerical value lying between 0 and 1; larger values indicate higher levels of assurance. In general, assurance will depend on the level of diversion d, the time span T over which the diversion occurs, and the removal strategy i.* In addition,

*Removal strategy attributes include the physical removal path, ancillary concealment techniques, etc.

assurance depends on the portion of the facility from which the diversion is taken. To fix this last parameter, we consider one MBA in isolation for the purpose of this analysis. We denote the overall assurance, that is, the assurance derived from all safeguards elements, for specified values of d, T, and i, by

$$A(d,T,i) \quad .$$

Qualitatively, A(d,T,i) may be thought of as a measure of the safeguards system's ability to provide an indication in accord with the true state of affairs, either no diversion or diversion. We consider next how A(d,T,i) might be constructed from a number of component assurances.

The first assurance component derives from materials accounting. We designate it a_{MA}, and it is related to the detection and false-alarm probabilities for the materials accounting system. For the case of one MBA, a_{MA} does not depend on i, the diversion removal strategy, but it is generally a function of d and T. Therefore, we denote the component assurance from materials accounting as

$$a_{MA}(d,T) \quad .$$

For $a_{MA}(d,T)$ to be nonzero, the IAEA inspector must have sufficient unfalsified (honest) data to verify a materials balance. The two possible sources of these data are the operator's accounting measurements and the inspector's independent accounting measurements. The inspector's measurements must be protected against falsification. In addition, the inspector may wish, or be constrained, to use some operator's measurement results as if they were unfalsified; those measurements also require protection. The remainder of the operator's measurements may have been falsified, but that possibility is covered by the inspector's materials accounting analysis techniques, based on sufficient independent measurements, as outlined in Sec. V.A ; Ref. 3, Appendix H ; and Ref. 17.*

*Note that a_{MA} depends on how the operator falsifies his own measurements that are verified only by the inspector's independent materials accounting measurements. The operator's falsification strategy will also depend on the inspector's capabilties and activities. We assume that the operator always chooses the optimum falsification strategy so that the dependence of a_{MA} on the falsification need not be shown explicity.

Component assurance that the inspector's measurements and a suitable subset of the operator's measurements are unfalsified will be designated a_{AI}, where the subscript stands for accounting information integrity. Because methods of falsification may depend on the diversion removal strategy (for example, multiple measurements of the same material at an output KMP) a_{AI} generally depends on i. Furthermore, a_{AI} may also be a function of d and T. Therefore, we denote the component assurance of accounting information integrity as

$$a_{AI}(d,T,i) \quad .$$

The term $a_{AI}(d,T,i)$ approaches one if the requisite accounting information has not been falsified.

The concept embodied in a_{AI} is broad enough to include the protection of measurements as they are made; the protection of data acquisition, treatment, and storage elements; and the protection of the accounting information validity by such means as seals. The techniques used to provide suitable values for a_{AI} have commonly been considered as part of the containment/surveillance system.

From this discussion, we may regard a_{MA} as a "conditional" assurance component, given an assurance, a_{AI}, of the the materials accounting information integrity in the sense described above. Assuming that assurances behave somewhat like probabilities, the composite assurance obtained from these two components, with no other safeguards elements active, can be expressed as the product

$$a_{MA}(d,T)a_{AI}(d,T,i) \quad .$$

This expression is only approximate, providing a lower boundary to the achieved assurance from the two elements. This occurs because the safeguards element providing a_{AI} has an additional capability to provide assurance against some types of diversions and falsifications by itself, without need for the materials accounting element. However, not all, perhaps very few, types of diversions and falsifications can be detected in this manner. For example, the divertor may decide not to tamper with the inspector's measurements, but falsify the unprotected operator's measurements and divert through a strategy not covered under a_{AI}. This method would be especially tempting if a_{MA} were judged to be low enough; in that case, there would be little reason to falsify.

Another component of assurance derives from the portion of containment/surveillance that we have called "surveillance of boundary penetrations." We denote this assurance component by a_{BPS}, and it is generally a function of d, T, and i, so that we can write

$$a_{BPS}(d,T,i) \quad .$$

We assume that the assurance component a_{BPS} is "independent," analogous to the statistical term, of all other safeguards assurances such as a_{MA} and a_{AI}. This assumption requires special care in deriving a_{BPS} to ascertain that a capability contibuting to a_{BPS} is not also "double-counted" as contributing to a_{AI}. For example, for a particular diversion strategy the assurance obtained from surveillance of an output penetration associated with a KMP should be ascribed only to a_{AI} or to a_{BPS}, not to both. If the surveillance serves to protect the KMP, and the KMP is necessary for materials accounting, then the corresponding assurance should be incorporated in a_{AI} to obtain a lower boundary on the true overall assurance. Furthermore, if the surveillance device provides quantitative measurements of materials flows, that information would be of value to the materials accounting system. At the same time, there would be a hidden contribution to the achieved value of a_{BPS} that would not appear in the calculation of a_{BPS}.

As with materials accounting, proper functioning of the boundary penetration surveillance system relies on the acquisition of unfalsified data. We call the assurance that such data are available a_{SI}, where the subscript stands for surveillance information integrity. Usually, it will be a function only of the removal strategy i, so that we may denote it by

$$a_{SI}(i) \quad .$$

Under the independence assumption, the assurance obtained from materials accounting, surveillance of boundary penetrations, and information integrity measures can be written as

$$1 - [1 - a_{MA}(d,T)a_{AI}(d,T,i)][1 - a_{BPS}(d,T,i)a_{SI}(i)] \quad .$$

This expression is analogous to that for the probability of either or both of two independent events. As before, we have conservatively ignored any additional assurance that might be obtained from any of the elements providing a_{SI} acting alone.

Other components of assurance may be derived, for example, from additional inspector activities. We combine these and call the corresponding assurance a_O. In general, a_O will depend on d, T, and i, so that we denote it by

$$a_O(d,T,i) \quad .$$

We further assume that a_O is independent of all other assurances. Therefore, the overall assurance obtainable from all the above elements, for one MBA and for specified values of d, T, and i, is

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

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

Although other formulations are possible, we take as our overall assurance the minimum of the assurances for all the diversion paths,

$$A(d,T) = \min_{i} A(d,T,i) \quad .$$

It must be emphasized that the assurance equation is only qualitative and does not imply that assurance values can or should be calculated. Its main function is to highlight the relationships among the various sources of assurance obtainable from IAEA safeguards. The equation shows that materials accounting and containment/surveillance must be, and of necessity are, closely intertwined in practical applications. They cannot be divided into separate and independent approaches between which a choice can be made.

Selection of the minimum assurance over all diversion removal strategies as the overall assurance has important implications. Because of the complexity of nuclear facilities, such as reprocessing plants, there can never be certainty that all diversion removal strategies are identified. Thus, any combined measure of safeguards performance can only give an assurance of detecting diversion or anomalies related to identified diversion strategies. Although the number of such strategies may be large, they can be reduced to a manageable number by a credibility analysis that eliminates those strategies requiring violation of a physical law or extraordinary operator resources for diversion. Diversion removal strategies that are so eliminated, but subsequently found to be credible in some manner, will require reassessment of the overall assurance, and perhaps modification of the safeguards system. Therefore, it is desirable to use those safeguards devices and elements that are least dependent on the diversion removal strategy. This approach also minimizes the need for design verification and periodic reverification to guard against clandestine facility modifications.

One important example occurs with respect to the assurances a_{MA}, a_{AI}, and a_{BPS} derived for the separations process, MBA 2, in a reprocessing plant. Although a_{AI} may depend on the removal strategy, the actual dependence (if any) is on a portion of the total strategy, such as for an output KMP, and the number of such KMPs and dependencies is relatively small compared to those required for a_{BPS} if it were applied to MBA 2. Furthermore, a_{MA} is independent of removal strategy. We believe that a less complex, less diversion-strategy-dependent system would be needed to support those near-real-time accounting measurement points not included in conventional accounting than would be needed for application of boundary penetration surveillance in MBA 2. For this reason, in this report we have proposed that for the separations MBA in the reference reprocessing plant, heaviest concentration should be on materials accounting and on assuring the validity of the necessary information.

We have not yet addressed the problem of obtaining values of all the assurance components, although some methods were discussed in Secs. V.A and V.B for a_{MA} and a_{BPS}. The major difficulty is that the information provided by the various safeguards elements can be fundamentally different. For example, a nonzero materials balance with a statement of its statistical significance, an indication by a portal monitor of materials presence exceeding some threshold, and a picture from a film camera showing an abnormal facility activity are all pieces of information giving qualitatively different information about diversion and differing in the degree of quantification of the missing amount. Thus, although the performance of the materials accounting system and some containment/surveillance instruments can be described as a probability of detecting some threshold amount of material, other containment/surveillance equipment such as cameras, seals, equipment enclosures, and tamper-protection devices provide diversion information that is subjective and not readily quantifiable in the same terms. Many of the devices and techniques that provide the component assurances a_{AI} and a_{SI} fall into this category and so have not been discussed.

VI. RESULTS, RECOMMENDATIONS, AND CONCLUSIONS

This report discusses an approach to coordinate nuclear materials accounting and containment/surveillance concepts that might provide an integrated safeguards system satisfying the requirements of the IAEA. AGNS' BNFP was used as the reference facilty.

A. International Safeguards Requirements

The main thrust of the international nonproliferation effort is to prevent the spread of nuclear weapons while promoting peaceful uses of nuclear energy. IAEA safeguards are basic to pursuing these goals. The effectiveness of IAEA safeguards is related to its capability to detect diversion of nuclear material by verifying the findings of the SSAC. The inspector's verification procedure is based on periodic examination of the materials balance equation for each MBA. The inspector must determine that

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

These verification activities include (1) examining safeguards-related information provided by the State, (2) collecting independent information by the IAEA, and (3) comparing the two sets of materials accounting information to determine the ability of the IAEA to establish the completeness, accuracy, and validity of the State's data. The IAEA uses methods drawn from materials accounting and containment/surveillance, augmented by an appropriate level of inspector presence, to implement its verification system.

B. Safeguards Concerns

The IAEA verification of the operator's nuclear materials accounting information is based on examining the materials balance equation to detect

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

Diversions hidden by measurement uncertainties are possible because statistical errors are always present in the measurements used to form the materials balance. Measurement uncertainties should be reduced to decrease the amount that could be diverted, but the estimate of measurement uncertainties also should be realistic to maintain false-alarm rates at an acceptable level.

Diversion hidden by falsification of operator's data, that is, falsification of suitable terms in the materials balance equation, could be achieved by

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

For MBAs in the reprocessing facility, falsifications are correlated among MBAs. For example, an overstatement of outputs from one MBA will result in an overstatement of inputs to the next MBA. Detection of diversion in one MBA is related to the adequacy of safeguards in adjacent MBAs, and correlation of verification activities and results among MBAs is important.

C. Verification Activities - General

The inspector examines safeguards information provided by the State for consistency and completeness both within each MBA and between MBAs. If data have been falsified at several measurement points and the falsifications have not been properly correlated, the examination may detect falsifications.

Collection of independent data by the inspector does not require that each sample or measurement reported by the State be duplicated. The inspector's concerns are that his data are sufficient to verify the State's findings and that his data are independent of the State's data. The inspector's values can be classified as those intended to verify

- particular values reported by the State and
- operator's measurement procedures.

Thus, the inspector must establish an independent analysis capability for each KMP. For those measurements at KMPs the inspector wishes to use as being unfalsified, he must ensure integrity of measurements by participation in measurement control programs and surveillance of measurement procedures, and he must ensure integrity of the operator's instruments with inspector-controlled surveillance devices.

The inspector compares the operator's and his own materials accounting data and examines information from the containment/surveillance system to obtain an assurance of nondiversion.

D. Summary of Verification Activities in the Reference Facility

The inspector will not duplicate all of the State's measurements, but will collect the minimum amount of data necessary for verification. The inspector may wish to verify particular values reported by the operator by obtaining samples that duplicate those of the operator and performing independent measurements. To ensure that valid samples have been taken and meaningful measurements have been made, the inspector may use (1) surveillance to monitor measurement procedures and the status of instruments and data, (2) surveillance of containment boundary penetrations to detect attempts to divert nuclear material or to bypass key measurement points, and (3) his own observations. We have assumed that the reference facility will accommodate continuous inspection and that the inspector will have on-site laboratory facilities.

1. Verification in MBA 1. For transfer and inventory measurements in the fuel receiving and storage area of MBA 1, the inspector will check the identity of the spent-fuel assemblies by reading the serial numbers or by interrogating FAIDs. He may also perform rapid qualitative measurements of assemblies (attributes check) or verify quantitative measurements of a limited number of fuel assemblies (variables test). These verification activities may be performed on assemblies in the cask-unloading pool, before the spent-fuel transfer tunnel, and in the spent-fuel storage pool during physical inventories. For qualitative and quantitative measurements, nondestructive techniques that employ Cerenkov-light, gross-gamma-ray, and neutron detection systems are available. In the chop/leach process area, the inspector should verify the calibration and operation of the leached-hulls monitor and observe the handling of the hulls until they are packaged and leave safeguards.

Surveillance of KMPs in MBA 1 includes spent-fuel monitors at the cask-unloading pool and before the entrance of the spent-fuel transfer tunnel, and optical surveillance in the spent-fuel storage area. Penetrations in the containment boundaries of the spent-fuel storage area and the chop/leach area are monitored to prevent bypass of KMPs.

Penetration monitoring can also be used to provide assurance, between physical inventories, that undeclared changes in the spent-fuel inventory could not occur without risk of timely detection and that removing amounts of dissolved fuel within the limits of error of MUF from the chop/leach area would also incur risk of detection.

2. Verification in MBA 2. The inspector's verification activities in MBA 2 (the separations and plutonium purification processes) are concerned with accurate volume, density, and concentration measurements to verify flow through KMPs and inventories in KMPs. For near-real-time accounting, flow measurements must be verified to estimate in-process inventory in strategic measurements points such as columns. The inspector must verify the calibration of tanks and the initial and subsequent calibration of the

operator's differential pressure instruments; he must also verify that representative samples were taken. The inspector will verify plutonium and uranium concentrations by independent measurements. For conventional materials accounting, verification activities are performed at the transfer and in-process KMPs such as the input accountability tank, high-level liquid-waste tank, solid-waste assay station, plutonium product sample tank, plutonium product recycle tank, the two feed adjustment tanks, and the 1BP surge tank. For near-real-time materials accounting, verification of the in-process inventories at strategic measurement points such as the HA feed tank; 3P concentrator; and the HS, 1B, 2A, 2B, 3A, 3B, and 3PS columns is required in addition to the activities at the conventional KMPs. This verification need not be of the same quality as that of transfer measurements because diversion by overstatement is limited by the amount of material in these containers and the maximum variability in inventory that is allowed without causing major process upsets.

The measurement procedures are monitored by surveillance instruments to prevent bypass or other manipulation of transfers. A data processing system is required to correlate the data from various sensors so that the proper sequence of operations can be monitored. The possible role of such a system was described.

3. Verification in MBA 4. For MBA 4 (the plutonium-nitrate storage area) verification of volume, density, and concentration measurements is required at the flow KMPs (the plutonium product sample tank, the plutonium product recycle tank, and the receipt tank in the plutonium conversion process area) and at all inventory KMPs. The in-process inventory measurements of the storage tanks may be improved by on-line measurement of the plutonium concentration. An on-line measurement could be made more frequently than a laboratory measurement and would reduce sampling errors. Penetrations in the containment boundary of MBA 4 are monitored to ensure that the KMPs are not bypassed and to detect unreported inventory changes in a timely manner.

E. Effectiveness of Verification Activities

The inspector must use his resources efficiently and effectively in verifying safeguards information. The effectiveness of the nuclear materials accounting system is established using statistically designed data evaluation techniques. Effectiveness in surveillance of containment boundary penetrations is determined by network analysis. These procedures also assist the inspector in planning inspection strategies.

1. Effectiveness of Materials Accounting. When analyzing his own and the operator's reported measurements for evidence that could indicate missing material, the inspector must consider that the operator's data may be falsified and that measurement uncertainties may hide diversion. This problem is treated in the report by applying the ISS that are sensitive to both data falsification and missing material. The performance of these statistics in detecting data abnormalities was evaluated for the chop/leach area of MBA 1, for MBA 2, and for MBA 4 over a range of diverted amounts. In each case the analysis assumed valid inspector's data and the optimal operator's data falsification strategy. Also, all of the detection sensitivities presented here assume that the inspector either has a measurement method with uncertainty comparable to the operator's method or can verify the operator's measurement and use it as his own. In all other cases, the inspector's detection probability is lower.

MBA 2 of the reference facility is the most likely area for application of these methods because quantities of material are relatively small and measurement techniques for this area are well developed. If the inspector uses his own data for missing material without regard to the operator's falsification, the sensitivity of ISS_2 to missing material meets the IAEA goal for detecting abrupt diversion, assuming that the inspector's and operator's measurement uncertainties are equal. For 8 kg of plutonium diverted in 7 days, the inspector, using ISS_2 to test for diversion, has a detection probability of 0.87. If the inspector has not verified all the operator's measurements, he must use a statistic (ISS_0 or ISS_1) to test for data falsification or diversion and accept a slight reduction in sensitivity. If he tests for falsification and diversion using ISS_1, the detection probability is 0.92.

Although the chop/leach area and MBA 4 have not traditionally been considered in near-real-time accounting, evaluation of the ISS in these areas shows that substantial probabilities of detecting missing material can be attained. In the chop/leach area, 8 kg of plutonium diverted in 7 days is detected with probability 0.64 if the inspector tests only for diversion hidden in measurement uncertainties, and it is detected with 0.56 probability using ISS_1 to test for diversion and falsification. For MBA 4 the respective probabilities are 0.26 and 0.21. The IAEA goals for detecting protracted diversion cannot be met in any of the MBAs because the goal quantity is only 0.05% of the annual throughput.

2. Effectiveness of Containment/Surveillance. Surveillance of containment boundary penetrations was considered as a safeguards measure to provide additional safeguards assurance for areas of a reprocessing plant where irreducible measurement uncertainties

or operational constraints preclude timely or accurate materials balance accounting. Accordingly, conceptual containment/surveillance systems of this type were designed for MBAs 1 and 4. A useful measure of the safeguards assurance is the probability of at least one alarm in the course of a diversion of a specific amount over a given time period, while specifying the associated false-alarm rate. Using data from sensor modeling for six generic sensor types, system sensitivity and false-alarm rate were computed for time periods ranging from 10 days to 360 days and for a range of diversion amounts. The results are summarized in Table XIX.

The results suggest that for MBAs 1 and 4 abrupt diversion of a significant quantity has a probability >0.95 of generating at least one surveillance alarm. In MBA 1, even protracted diversion of a significant quantity has a high risk of generating a containment/surveillance alarm.

Another role for containment/surveillance involves verifying measurement information for the inspector. Materials balance accounting for safeguards as discussed in Sec. V.A combines potentially falsified measurement information supplied by the operator and verified measurement information obtained by the inspector to decide whether significant quantities of material have been diverted from an MBA. Surveillance methods that may be useful in verifying critical measurement information were discussed in Sec. IV. Preliminary analysis of potential falsification scenarios suggests that fairly extensive surveillance systems may be required. However, there is no generally accepted methodology for designing or evaluating surveillance systems for measurement verification, and thus it is impossible to estimate the effectiveness of such systems.

3. Quantifying the Assurance for Materials Accounting and Containment/ Surveillance. The overall assurance is a combination of the assurance

- provided by materials accounting, $a_{MA}(d,T)$;
- of materials accounting integrity, $a_{AI}(d,T,i)$;
- provided by surveillance of boundary penetrations, $a_{BPS}(d,T,i)$;
- of surveillance information integrity, $a_{SI}(i)$; or
- provided by additional inspector activities, $a_O(i)$.

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

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

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

The factors contributing to this equation are difficult to quantify; hence, it can only provide a qualitative indication of the relationship among the components of assurance. Because the assurance derived from the materials accounting system is the only one independent of diversion path, a heavy reliance has been placed on ensuring the validity of materials accounting information.

F. Recommendations

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

1. Verification Approach. An approach to the inspector's verification of safeguards data for a reprocessing facility was developed. This approach incorporates

- appropriate statistical test procedures for materials accounting data from each MBA to detect abrupt diversion of a significant quantity of nuclear material,
- surveillance of the containment boundary penetrations for MBA 1 and MBA 4,
- surveillance of KMP measurement devices and procedures for all MBAs,
- inspector participation in the measurement control program for materials accounting and surveillance instruments, and
- an on-site inspector analytical laboratory with appropriate analytical instruments and standards.

2. Facility Design to Improve Verification Effectiveness. The safeguards system performance requirements should be evaluated at the facility design stage so that they can be appropriately included with other considerations such as process design, operating economics, health and safety, technical safeguards capability, and Agency resources. Materials accounting and containment/ surveillance should be designed and integrated in a manner that will allow the most reasonable compromise between safeguards performance goals and these constraints.

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

- relative accuracy between input and output measurements (the limiting factor will be the uncertainties in the relative bias between reference materials and methods used for measurements);
- precision and relative accuracy of cleanout physical inventory measurements;
- redundant methods at KMPs to reduce systematic errors; and
- for near-real-time accounting, the precision of in-process inventory estimates and measurements.

Features of importance to containment include

- the number of penetrations through MBA containments,
- identifying and verifying required penetrations,
- providing multiple containment boundaries where feasible,
- a penetration design to minimize surveillance requirements,
- the use of containment to provide a barrier between men and nuclear material, and
- incorporating containment boundary design and maintenance philosophy.

The important features for surveillance are

- surveillance device sensitivity and an acceptable false-alarm rate;
- surveillance device reliability and, where necessary, redundancy and variety to aid in resolving anomalies;
- surveillance device provision in facility design; and
- tamper protection of surveillance devices.

Features of importance to the inspector include

- assurance that all significant nuclear material flows and inventories are accessible for verification at KMPs and
- assurance that the inspector is provided a sufficient set of unfalsified data.

G. Conclusions

This report identifies international safeguards system elements designed to provide assurance that diversion from a large scale reprocessing plant cannot occur without significant risk of timely detection. Near-real-time accounting and penetration-monitoring systems were proposed and evaluated for areas of the plant where additional safeguards assurance beyond that provided by verification of conventional materials accounting may be desirable.

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

The safeguards assurance derived from the materials accounting system depends on the effectiveness of the inspector's verification activities. Surveillance measures that may aid the inspector in verifying measurement information are identified in this report. It seems likely that extensive surveillance systems will be necessary to provide the required level of verification. However, no systematic method for designing or evaluating measurement verification systems exists. A continuing effort will be necessary to develop these techniques and demonstrate that measurement at KMPs can be verified.

Penetration-monitoring systems potentially can provide a high level of safeguards assurance that abrupt diversion from MBA 4 and abrupt or protracted diversion from MBA 1 would trip a surveillance alarm. However, in practice, this assurance will depend upon the successful development of surveillance devices having performance characteristics similar to those attributed to the generic devices considered in this report.

Selected components for an inspector-verifiable near-real-time accounting system and for containment/surveillance systems have been installed and are being evaluated as a continuing safeguards demonstration program at the AGNS BNFP. Continuation of this program is necessary for international acceptance of the system.

A single figure of merit for the aggregate safeguards system was not developed in this study. No known method exists for properly quantifying the interdependencies of the the various safeguards techniques. The stated performance of materials accounting and containment/surveillance is, of course, dependent on adequate assurance of valid inspector's data, and that assurance is not yet quantifiable. Thus, this report has emphasized the functional definition of appropriate safeguards system elements for a large-scale reprocessing plant.

ACKNOWLEDGEMENTS

The authors are indebted to the technical staff of Allied-General Nuclear Services, and particularly to John Ellis, Mike Ehinger, Ken Plummer, and John Crawford for their work in implementing advanced safeguards concepts at BNFP; for providing technical assistance in evaluating penetration-monitoring systems; and, with L. D. Barnes, for reviewing this report.

The authors gratefully acknowledge the helpful suggestions and criticism of G. A. Hammond, G. D. Smith, and J. A. Goleb of DOE/OSS; W. A. Higinbothamn and A. Waligura of Brookhaven National Laboratory; C. Bennett of the Battelle Human Affairs Research Center; R. J. Dietz of Los Alamos National Laboratory; and J. M. deMontmollin, W. F. Hartman, and T. A. Sellers of SNLA in reviewing the manuscript.

L. D. Robertson and M. T. Head of Science Applications, Inc. provided assistance in implementing the penetration-monitoring methodology.

The patient efforts of Sharon Klein in typing and revising the numerous drafts of the report are gratefully acknowledged. Carole Oldenborg ably assisted with preparing the final manuscript.

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APPENDIX A

SOME MEASUREMENT TECHNIQUES FOR MATERIALS ACCOUNTING

by
R. G. Gutmacher

The discussion of detailed concepts of integrated safeguards in Sec. IV listed some possible measurement techniques and instruments for use at the KMPs. In this appendix, these techniques and instruments are described in greater detail.

I. NONDESTRUCTIVE METHODS FOR SPENT-FUEL ASSAY

Nondestructive techniques for spent-fuel assay are based on the measurement of the gamma-ray or neutron signatures of the fission and activation products and the actinide inventory in the spent-fuel assembly. All of the techniques involve the direct measurement of radiations emitted by the irradiated fuel material, except for the Cerenkov-light technique that measures secondary radiation. Nondestructive methods for spent fuel were recently reviewed,[1-3] and the following discussion is based on those reviews.

A. Gamma-Ray Techniques

Gamma rays originate from the fission and activation products and the actinides, with fission and activation products being the principal gamma-ray sources. The gamma-ray dose rate ranges from 10 to 30 000 R/h after approximately 1-yr cooling time. The gross-gamma-ray signature can be measured using ion chambers,[4] scintillators,[5] and thermoluminescent detectors (TLDs),[6] or it can be measured indirectly from the Cerenkov-light emission.[7]

Cerenkov light, a continuum extending into the blue region of the visible spectrum, results from the interaction of direct radiation with the surrounding material. Measurements of Cerenkov light do not require placing any device in the water, because the light intensity is measured above the surface of the storage pool. This permits rapid verification of radioactive material in fuel assemblies, and an approximate check of the declared exposure and cooling time. Recent results with this technique are described in Ref. 8.

Measurements of Cerenkov light require that the ambient light level be reduced around the storage pool and that the fuel assembly not be stored in a canister. The other gross-gamma detectors are not limited by these restrictions. However, measurements of the gross-gamma-ray signatures using ion chambers, scintillators, or TLDs require underwater fixtures in the fuel storage pool.

The use of detectors that are sensitive to gamma-energy thresholds, for example Be(γ,n) detectors, provides the capability of rapidly measuring the presence of specific fission products.[9] Gamma rays having energies greater than 1660 keV interact with beryllium to produce neutrons that can be counted using a ^{235}U fission chamber. The principal gamma ray contributing to the production of neutrons by the (γ,n) reaction is the 2186-keV gamma ray from the ^{144}Pr fission product ($t_{1/2}$ = 17 minutes), which is in secular equilibrium with its parent ^{144}Ce ($t_{1/2}$ = 284.5 days). This technique provides information about the presence of a fission product ; therefore, it provides a higher level of verification for spent-fuel assemblies than that provided by gross-gamma measurements.

High-resolution gamma-ray spectrometry (HRGS) is the most widely accepted safeguards technique for examination of spent-fuel assemblies.[10] By using isotope activities and ratios, for example ^{137}Cs or $^{134}Cs/^{137}Cs$, the exposure values of assemblies can be predicted with precisions of 5-10%, if the irradiation histories are known.[11] This technique can also be used to establish the consistency of cooling times for a specific set of fuel assemblies. The use of HRGS is limited by self-shielding of the fuel assembly because HRGS only "sees" the outer few rows of fuel rods in an assembly. Gamma rays used for HRGS usually are in the energy range 600-800 keV and are significantly attenuated. Another limitation is the complexity of the equipment required to perform these measurements. Collimating fixtures must be placed in the storage pool and the fuel-scanning geometry must be controlled to obtain high-quality results.

B. Passive Neutron Techniques

The passive neutron technique for verification of irradiated fuels is similar to the Be(γ,n) technique, in that information is obtained about the presence of specific isotopes. It is also similar to the HRGS technique, in that the passive neutron signatures can be correlated with exposure.

An important advantage of neutron measurements is the penetrability of the neutrons. Calibrations have shown that fuel rods in the center of a PWR assembly contribute about as much to the neutron signature as the exterior rods[12] because the effects of neutron attenuation and multiplication are approximately compensating.

Passive neutron signatures may also be correlated with the production of plutonium in irradiated fuel assemblies. Another advantage is the relative simplicity of the passive neutron measurement, which requires only a fission chamber, power supply, and scaler/timer.

Measurements of the relative neutron rates of irradiated fuel assemblies have been correlated with declared exposure values. A power-law functional relationship was used: neutron rate = $\alpha(\text{Exposure})^{\beta}$, where α and β are empirically determined constants.[11-13] Typical values of β are in the range 3.0 to 4.3, depending on the cooling time and type of reactor.

C. Active Neutron Techniques

Active neutron-interrogation techniques are being developed to determine the fissile contents of spent-fuel assemblies.[14-16] An external neutron source, either an accelerator source or an isotopic neutron source, induces fissions in the fissile isotopes ^{235}U, ^{239}Pu, and ^{241}Pu. By measuring the prompt fission neutrons, an estimate of the fissile content can be obtained. Fast fission in ^{238}U has been estimated to be about 7% of the total count rate and is only slightly dependent on exposure.[17] If prompt and delayed neutron signatures can be separated, the relative concentrations of the uranium and plutonium fissile isotopes may be calculated. If the fuel assembly can be removed from an aqueous environment, other assay techniques can be applied.[15,16] The active neutron technique has one distinct advantage over the techniques discussed previously: the fissile material is measured directly. The other nondestructive techniques measure signatures that may be correlated with fissile inventory.

II. NONDESTRUCTIVE METHODS FOR LEACHED HULLS

Leached hulls are measured to determine the quantity of undissolved uranium and plutonium remaining in the hulls. The measurement of leached hulls was reviewed in detail.[18] Most hull-monitoring systems involve the measurement of fission-product activities that can be related to the quantity of fissile material remaining in the hulls. Most leached-hull monitors have been designed to measure the amount of the fission product ^{144}Ce by specifically counting the 2186-keV gamma ray of its daughter ^{144}Pr. That gamma ray, by virtue of its high energy, has the least interference from radiation of interfering isotopes that may be present. However, because the half-life of ^{144}Ce is only

284.5 days, that signature cannot be used to measure hulls from fuel with a very long cooling time, generally of the order of 3-4 yrs. For such fuel, gamma rays of ^{134}Cs, ^{137}Cs, or ^{154}Eu could be used.

Hull disposal containers could possibly be used to divert large quantities of clean plutonium. The high gamma-radiation level of a hull container would not be significantly affected by the addition of kilogram quantities of plutonium. If passive neutron techniques are used, the quantity of concealable plutonium is reduced to several hundred grams. A monitor designed to count spontaneous fission neutrons has been described.[19] The advantages and disadvantages of passive neutron measurements and delayed fission neutron activation measurements were discussed in Ref. 18. Active neutron measurements offer a direct measurement of total fissile content and do not rely on any assumed relationship of fissile content to fission products or other actinides.

III. MEASUREMENT TECHNIQUES FOR PROCESS AND PRODUCT SOLUTIONS

The techniques discussed in this section include the in-line measurement of volume and density; some analytical methods for plutonium and uranium, such as isotope-dilution mass spectrometry, x-ray fluorescence and x-ray absorption edge densitometry, electrometric titrations, and spectrophotometry; and the assay of plutonium solutions by gamma-ray spectroscopy.

A. Volume and Density Measurements

The liquid level and density of solutions in process and storage tanks are measured with a pneumatic bubbler system, also called dip-tube manometers or pneumercators. The pressure differences between ends of purged dip-tubes are measured with precision equipment. Three pressure probes are required: one probe extends to near the bottom of the vessel, the second ends at a known elevation above the lower probe, and the third terminates in the vapor space of the tank. The dip-tubes are connected to differential pressure transmitters and are purged continuously to prevent the entry of process solution and vapors into the tubes. Rotameters are adjusted to give equal flow of dry air or nitrogen in each probe.

The differential pressure between either of the two lower probes and the vapor space probe is proportional to the liquid level, whereas the differential pressure between the two lower probes is proportional to the solution density. For differential pressure measurements an electromanometer or a precision pressure transducer with digital output is recommended. Direct computer-compatible output can be obtained from these instruments. The use of a liquid manometer is not recommended because of the possibility of operator error in reading and in transcribing measurement results. Given values for the liquid level and density, one may calculate the solution volume from an experimentally determined relationship between liquid level and volume for each tank. Volume calibration techniques are described in Refs. 20 and 21. If the measurements are made at a different temperature than the calibration, a correction must be applied.

B. Isotope-Dilution Mass Spectrometry

Mass-spectrometric measurement of elemental concentration may be performed by the method called isotope-dilution mass spectrometry (IDMS). For accountability measurements in a reprocessing plant, IDMS is chiefly used to determine the plutonium and uranium concentrations (and isotopic compositions) in the accountability tank, the feed adjustment tanks, and the high-level liquid-waste sample tank.

IDMS[22-29] involves adding a measured quantity of a highly enriched isotope, which is either not present or present at small relative levels in the sample, to an aliquot of the sample. This added element of known isotopic composition is termed the "spike." After chemical and isotopic equilibration, the quantities of the isotopes in the sample are measured relative to the added isotope by mass spectrometry. From the change in the isotopic ratios of the sample caused by the spike, the elemental content of the sample may be calculated.

The basic steps in an IDMS procedure are

(1) obtaining and preparing a representative and accurate aliquot of the sample,
(2) adding accurately known amounts of the spike isotopes to the sample aliquot,
(3) achieving identical chemical states of the isotopes and isotopic equilibrium between the sample and spike prior to any chemical separations,
(4) separating the uranium and plutonium from each other and from fission products and americium, and
(5) carrying out the mass-spectrometric analysis and subsequent calculations.

The conventionally used spike isotopes are ^{233}U and ^{242}Pu. With increasing burnup of the fuel and the consequent increased formation of ^{242}Pu in the fuel specimen, this isotope becomes less desirable as a spike. If the abundance of ^{242}Pu in the fuel is 5-10%, ^{242}Pu can still be used as a spike isotope, but an unspiked sample must, of course, be analyzed to correct for the amount of ^{242}Pu originally present. A more ideal spike isotope in this case is ^{244}Pu.

In some procedures, plutonium and uranium remain together after separation from fission products and americium and are sequentially analyzed in the mass spectrometer by increasing the filament temperature. Prominent among these procedures is the resin-bead technique,[30-33] in which plutonium and uranium are sorbed on a few anion-exchange resin beads, and a single resin bead is loaded into the mass spectrometer. The technique was recommended for use by Agency inspectors in the preparation of samples that will be analyzed by mass spectrometry at a distant laboratory. The beads can be packaged and shipped without the need for shielding.

A mass spectrometer is a complex instrument. Its operation and the performance of prior chemistry require skilled, careful personnel. Standard reference materials must be analyzed during each shift. In conventional IDMS, accuracies of 0.5% relative and precisions of 0.6% RSD have been achieved; the resin-bead technique has been reported to give an accuracy of 0.5% relative for the isotope-dilution measurement of plutonium and uranium concentrations in synthetic dissolver solutions.[34] The internal precisions were 0.9% RSD for plutonium and 0.6% for uranium.

C. X-Ray Fluorescence

X-ray fluorescence (XRF) techniques have long been applied to determine the actinide elements. The techniques are sensitive and accurate (microgram quantities may be measured with relative accuracies of 1% or better) and frequently require little or no sample preparation. Typical analysis times are short (0.5 h or less). The theory and practice of XRF analysis are reviewed in detail in the Refs. 35-39.

Much work has been done recently on the analysis of irradiated nuclear fuel dissolver solutions and of process and product solutions encountered in a reprocessing plant. An overview is given in Table A-1, and a brief discussion of some work in this field follows.

Several systems have been developed to assay highly radioactive spent-fuel solutions. One of these systems[41,43] uses a wavelength-dispersive spectrometer to assay solutions with uranium-plutonium ratios of 50:1 to 300:1. Accuracies and precisions of better than 1% have been obtained with analysis times of 2-5 min. Solutions having activities up to 1000 Ci/L are handled routinely by evaporating small samples onto a filter paper.[42] The maximum activity on the filter paper is 10 mCi. No shielding is necessary and there is no interference by radioactivity with the XRF measurement. If the

TABLE A-I

SOME APPLICATIONS OF XRF SPECTROMETRY TO SOLUTIONS OF IRRADIATED FUELS

Type of Sample	Concentration Range	Radiation Levels	Recovery[a] or Accuracy	Precision, RSD	Comments[d]	Ref.
FBR fuels, after partition	Pu=1-20 g/L	1 Ci/L[b]	Acc=1%	1%	Internal std.: Y WD	40
LWR dissolver solution	U=0.05-18 mg/g Pu=0.6-1.2 mg/g	1.3 Ci/g	Rec. U=97.8-105.2% Pu=98-102%	1-3%	Internal std.: Th WD Sample analyzed as solution	41
FBR fuels, dissolver solution or organic extract (1M nitric acid or 20% TBP-80% dodecane (v/v)).	1-200g U,Pu/L	<1000 Ci/L	----	1% (Conc >10 g/L)	Internal std.: Th solution deposited on filter paper.[c] WD.	42
LWR dissolver and product solutions	Dissolver U=14-220 mg/g Pu=0.5-1.5 mg/g Product U=280 mg/g Pu=1.6-46 mg/g	<1000 Ci/L	Acc=0.58% 0.95% 0.3% 0.53%	0.45% ---- 0.75% 0.45%	Internal std.: Th WD	43
Dissolver Solution	U=50 g/L Pu=0.12-0.62 g/L	2 Ci/g	Acc=2%	1%	Ti external std. ED Sample deposited on polycarbonate substrate	44
LWR Fuels	U=20-40 g/L Pu=0.2-0.4 g/L	1000 Ci/L		1%	WD	45
Product Solution	Pu,U=0.001-4 g/L	100 Ci/L		0.3%	ED, Pyrographite scattering chamber. Selenium monitor.	46
Product Solution	Pu,U=1-200 g/L	2.8mCi/gPu	Acc=0.3%	----	^{57}Co sources excite K x-rays of U and Pu. ED. Spectrum unfolding required to separate $PuK\alpha_2$ from $UK\alpha_1$.	47
LWR dissolver Solution	U=300 g/L Pu=3 g/L	1000 Ci/L	----	0.5-1%	Monochromator plus WD Spectrometer. Sample circulates from tank through sample cell. On-line automated system - under development.	48

[a]% Recovery = (quantity found/quantity taken) x 100.

[b]Maximum activity of analytical sample: 10 mCi/L

[c]Maximum activity on filter paper: 10 mCi.

[d]Acc = Accuracy
Rec = Recovery
WD = wavelength-dispersive spectrometer
ED = energy-dispersive spectrometer.

initial sample solution has > 10 mg of uranium, plutonium/mL, the reproducibility of the measurements is within 1%. Samples having low beta-gamma activities can be analyzed directly in solution after addition of an internal standard. The fission products cause no serious line interference. An automatic sample-preparation system is being developed to allow on-line analysis.[43]

Uranium and plutonium in solutions that have beta-gamma activities to 1 Ci/L have been measured directly through a Plexiglas window.[40] The system used is as close to in-line analysis as one can devise. An automatic sampler removes solutions from the sample line, and yttrium is added to serve as an internal standard. Solution transfers are made by pneumatic tube. A minicomputer performs data reduction and overall precision and accuracy of better than 1% are claimed for the technique.

In another system,[44,49] hot dissolver solutions containing uranium and plutonium at ratios up to 400:1 and uranium concentrations of ~50 g/L are measured with a low-powered x-ray tube in combination with a Si(Li) detector. Preliminary tests indicated that accuracies of 2% and precision of 1% RSD are possible with 10-min analysis times. However, accuracies of only 3% were obtained because of problems in sample preparation.

A system also has been developed for automatic sampling and sample preparation of dissolver solutions from the reprocessing of thorium-uranium fuels[50] and could be applied to uranium-plutonium fuels. For solutions emitting up to 2000 Ci/L, samples containing 1.0 mL of solution are automatically aliquoted and mixed with an internal standard. The aliquots are evaporated onto a filter paper, which is transferred to a shielded x-ray spectrograph. All operations are performed remotely under computer control.

The introduction of stable x-ray generators[51] that can operate to 200 keV and the use of ^{57}Co gamma-ray sources[52,53] have increased interest in K XRF analysis of uranium and plutonium. X-ray generators provide a significant improvement in peak-to-background intensity compared to radioactive sources such ^{57}Co. The primary advantage in using the K x rays results from the ability to use normal process materials such as stainless steel for cells; thus, in-line analysis is possible. The method is proposed for analysis of samples at any step of reprocessing from dissolver solutions to final product. Precision of better than 0.5% is anticipated where adequate peak-to-background intensity is obtainable.

D. X-Ray Absorption-Edge Densitometry

X-ray absorption-edge densitometry is an element-specific analytical method that can be applied in-line, at-line, or off-line to many process measurement needs. In this technique the transmitted intensity through the sample is measured for two x rays or gamma rays selected above and below an absorption edge for the element determined. For determining uranium and plutonium, both K- and L_{III}-absorption edges can be used. The L_{III} edge is useful for uranium and plutonium concentrations below ∿ 100 g/L. The K edge allows greater versatility in selecting cell materials and cell thickness and, thus, is applicable over a wider concentration range in process-type cells. With proper selection of cell path length and absorption edge, the method is applicable to concentrations in the range 1-500 g/L.

Instruments using K and L_{III} edges have been developed at the Los Alamos National Laboratory for determining uranium and plutonium in a variety of process samples.[54] A radioactive ^{169}Yb source is used for routinely determining uranium in the 100-400 g/L range. The precision is better than 0.5%. For the determination of plutonium, a radioactive ^{75}Se-^{57}Co source is employed. Field tests at Tokai-mura, Japan, have demonstrated a precision and accuracy of 0.3% over the concentration range of 150-300 g/L.[55,56] A K-edge instrument designed by Lawrence Livermore National Laboratory and evaluated at AGNS gave a precision of 0.5% for the design concentration range of 150-300 g/L.[57-59] An on-line K-edge densitometer designed for lower concentration, typically 30 g/L, is being evaluated at the Savannah River Plant. Solution is circulated from process tanks through a 7-cm path length cell. Well- characterized control samples having concentrations in the range 25-40 g/L were analyzed with a precision of 0.3%.[60]

An L_{III}-edge instrument using an x-ray generator as a source to permit simultaneous determinations of uranium and plutonium was designed at Los Alamos for the Savannah River Laboratory.[61] Precision and accuracy of 0.25% can be achieved at the optimum concentration of 50 g/L.

A versatile densitometer that can be applied to K- or L-edge analysis using x-ray tube excitation has been designed and evaluated at Karlsruhe.[62] Proposed applications include determination of uranium in accountability tank solutions and both uranium and plutonium in intermediate process and final product solutions. The x-ray tube excitation approach to absorption-edge densitometry also is being developed in the United Kingdom.[63]

E. Electrometric Titration Methods

Both uranium and plutonium can be determined with high precision and accuracy by the use of titrations involving oxidation-reduction reactions. Electrometric methods are classified by the technique used to detect the titration end point, such as potentiometric, amperometric, or coulometric. All of these methods can provide RSDs of better than 0.1%.

Potentiometric titrations measure the change in the system's potential as a component is removed by oxidation or reduction. Amperometric titrations measure the change in current between two electrodes that are maintained at a constant potential as titrant is added. Controlled-potential coulometry is based on the principle that the weight of a substance oxidized or reduced at an electrode is proportional to the quantity of electric charge passed through the electrode.

In controlled-potential coulometry the potential of the electrode is maintained at a constant value, relative to a reference electrode, to minimize the number of reactions that can take place. Interference from the reactions occurring at lower potentials can be eliminated by performing a preliminary coulometric titration at a potential such that those reactions have occurred before measurements are started. Reactions requiring higher potentials cannot occur. Both uranium and plutonium can be titrated in the same sample without separation by performing successive titrations at different potentials. Generally, controlled-potential coulometry requires smaller samples than potentiometric or amperometric titrations. Reviews of the coulometric determination of plutonium are given in Refs. 64-65. A highly selective method and automated equipment are described in Refs. 66-67.

For the electrometric determination of plutonium, the plutonium may be oxidized quantitatively to Pu(VI), then titrated to Pu(IV); this couple is preferred if uranium or iron is present. Oxidants for the first step include AgO and $HClO_4$. In the most widely employed potentiometric and amperometric methods, a standard ferrous-sulfate solution is the reductant.[68] In several procedures, an excess of ferrous sulfate is added and back-titrated with a standard Ce(IV) or dichromate solution.[69-71]

Alternatively, plutonium can be determined by quantitative reduction to Pu(III) and subsequent titration to Pu(IV). Most controlled-potential coulometry procedures use this couple.[66,67,72-74] The reduction and subsequent oxidation are performed electrolytically, and the current required for the oxidation is integrated over time. The coulometer is calibrated with National Bureau of Standards (NBS) plutonium metal. The sample required is 5-15 mg of plutonium, the time per analysis is about 30 min, and a precision of 0.1% RSD can be achieved.

A 1.0 N sulfuric acid solution is frequently used as the supporting electrolyte because any Pu(VI) present can be reduced quantitatively to Pu(III) in that medium.[64]

However, iron interferes quantitatively and must be determined separately, so that a correction can be applied.

F. Spectrophotometric Methods

Spectrophotometric methods rely on the principle that a compound or complex in solution will absorb light of a specific wavelength in a quantity proportional to the concentration of the measured species. Generally, the concentration-absorbance function is a simple proportional relationship expressed by Beer's law, but variations may result at high concentrations or when other competing reactions occur. The precision attainable by direct spectrophotometric methods usually is 0.5% RSD or more and is seldom better than 0.2%. However, it can be improved to 0.05% with differential techniques that compare the absorbance of the unknown to a precisely known reference. The differential spectrophotometric method of determining plutonium[75] can be used for plutonium-nitrate product with precision and accuracy equivalent to that obtainable by the best electrometric methods for the analysis of scrap material.[76]

A rapid off-line spectrophotometric method has been described for determining plutonium in dissolver and other reprocessing samples.[77] Plutonium is oxidized to the hexavalent state using AgO; neodymium is added as an internal standard; and plutonium and neodymium absorbances are measured in the near-infrared region. Fission-product activity to 500 Ci/L and uranium concentration to 400 g/L do not interfere for determining 1-5 g/L of plutonium. Precision of better than 1.5% (1σ) and an accuracy of 0.5% are claimed; the analysis time is 1 h.

Most chromogenic reagents that react with plutonium also yield intensely colored species with uranium and many fission products; therefore, if plutonium is to be determined in reprocessing samples, a separation is required. For low-plutonium concentrations, methods such as XRF, alpha, or gamma spectrometry may be preferred. However, the tetrapropylammonium method is interesting[78] because uranium and plutonium can be determined sequentially in the same sample. The method has been automated.[79]

Spectrophotometric methods for determining uranium in reprocessing streams generally are limited to measuring trace concentrations of uranium in waste streams and possibly in the final product plutonium. The method for determining uranium with 2-(2-pyridylazo)-5-diethylaminophenol (PADAP) has been modified specifically for determining uranium in reprocessing-plant waste streams[80] and in plutonium-nitrate and oxide products.[81]

The uranyl-nitrate method[82,83] used for in-line process control is sensitive to variations in nitric acid concentration and temperature and lacks the precision required for safeguards applications. Browning of the optics can be a serious problem in process streams containing fission products. However, by measuring absorbance at two wavelengths with an on-stream detector, the method has been adapted to measure uranium concentration in-line with a precision of 3%.[84]

G. Assay of Plutonium Solutions by Gamma-Ray Spectroscopy

Several assay systems based on high-resolution gamma-ray spectroscopy of the naturally emitted plutonium gamma rays have been described. Plutonium-242 does not emit useful gamma rays and generally must be estimated or determined by a different method. Each system uses a very high resolution Ge(Li) detector. One system[85] is able to determine ^{239}Pu and ^{241}Pu over a plutonium concentration range of 0.5-500 g/L. Precision (RSD) and accuracy are claimed to be 1% or better for assays requiring 45 min or less. Sample self-attenuation is corrected by measuring the transmission of an external plutonium source through the sample. The assay procedure is insensitive to the density and chemical composition of the solutions, including the presence of uranium and other heavy elements. Modest amounts of fission product gamma-ray activity ($\leq$ 100 µCi/g of plutonium) are also tolerated. A simplified version of this instrument that measures the 414-keV gamma ray emitted by ^{239}Pu has been described.[86] The isotopic abundance of ^{239}Pu must be known.

In a different approach, the gamma rays of ^{238,239,240,241}Pu in the complex 100-keV region are measured and the composite spectrum is fitted with response functions for each isotope.[87] This method has been used very successfully for dilute solutions, for which attenuation corrections are small. This approach was combined with a differential transmission measurement for an on-line concentration monitor.[57,88]

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APPENDIX B

IMPLEMENTING THE INSPECTOR'S SUFFICIENT STATISTIC IN MATERIALS ACCOUNTING

by
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I. INTRODUCTION

The statistical procedures used to calculate the false-alarm probabilities (critical regions, a subset of the sample space corresponding to the rejection of the hypothesis being tested) and to compute detection probabilities (the power of the test) for materials accounting are sufficiently new and complex that they require a comprehensive explanation. Three cases are presented, based on formulation of an inspector's verification problem where both diversion and falsification are possible.[1,2] The objective is to outline a procedure for determining critical regions and power curves when testing the null hypothesis H_0 of zero diversion and zero falsification vs the alternative hypothesis H_1 of positive diversion, positive falsification, or both. The development is an extension of the ISS, which is given in Refs. 1 and 2.

II. ISS - GENERAL BACKGROUND

The operator can hide diversion in measurement uncertainties or through falsification of his reported data; therefore, it is important that the inspector use a test statistic that protects against both possibilities. Consider a single balance period and an MBA having true initial and final inventories I_0 and I_1, and true input and output transfers T_0 and T_1. The operator measures these quantities, perhaps diverts some goal quantity of material, and then reports to the inspector the possibly falsified inventory and transfer measurements. For the reference process the initial and final inventory measurements (I_0 and I_1) will each be the sum of measurements made on several process vessels, and the input and output transfer measurements (T_0 and T_1) each will be the sum of many individual transfer measurements.

The inspector either makes his own independent measurements or verifies the operator's measurements with containment/surveillance devices. This ensures the integrity of measurement instruments. Measurement procedures are observed with surveillance devices or simply by having the inspector present. The inspector's inventory measurements are denoted by I_0 and I_1 and T_0 and T_1 for inventory and transfer, respectively. Again, these measurements are sums of individual measurements.

If the measurement errors have normal distributions, the natural logarithm of the likelihood ratio, called the ISS, can be separated into two distinct, statistically independent terms, each distributed as a chi-square variable. These quantities may be used to test the composite hypotheses of (1) diversion, (2) falsification, or (3) diversion and falsification.

A. Statistical Testing

The ISS may be used to test the null hypothesis H_0 of no data falsification and no diversion of nuclear material against the alternative hypothesis H_1 that material has been diverted and/or that data have been falsified. Hypothesis testing requires that the null hypothesis and an alternative hypothesis be specified along with an acceptable false-alarm probability α. We say that we have insufficient evidence to reject H_0 if the test statistic falls outside the critical region of the test. On the other hand, if the test statistic falls inside the critical region when there is no diversion and/or falsification, we have accepted H_1 when, in fact, it is false. This incorrect decision occurs 100α percent of the time.

We accept H_1 when the test statistic falls in the critical region. As we have seen, the test statistic can fall in the critical region with probability α when there is no diversion. Therefore, we would like to quantify the probability of accepting the alternative hypothesis when it is true. This probability, $1 - \beta$, is called the power of the test, or detection probability, and depends on H_1 and the false-alarm probability. The probability of rejecting H_1 when it is true is designated by β. Thus, it is necessary to know the distribution of the test statistic both under H_0 and under the alternative hypotheses at a given significance level. For a given H_1, then, we reject H_0 if the test statistic falls in the critical or rejection region of the test. If we reject H_0 when it is true, we commit what is known as a Type I error with probability α, which is the significance of the test or false-alarm probability. On the other hand, if we reject H_1 when it is true, we commit what is called a Type II error. The probability of a Type II error is a function of the alternative hypothesis and the false-alarm probability.

Figure B-1 illustrates the relationship between α, $1 - \beta$, and the boundary of the critical region for diversion equal to 0 and 3. Each curve is a probability density function (pdf) for a normally distributed random variable. The left pdf (H_0 true) represents no diversion, whereas the right pdf (H_1 true) represents diversion of three units. The area under the H_1 pdf, to the right of the central region boundary, is $1 - \beta$, whereas the area under the H_0 pdf, to the left of the central region boundary, is α. The normal curves were used for illustration of diversion only, with no consideration for falsification.

In applying this procedure to materials accounting, we test the hypothesis

H_0:falsification = 0 and diversion = 0

against the alternative hypothesis

H_1:falsification > 0 and/or diversion > 0.

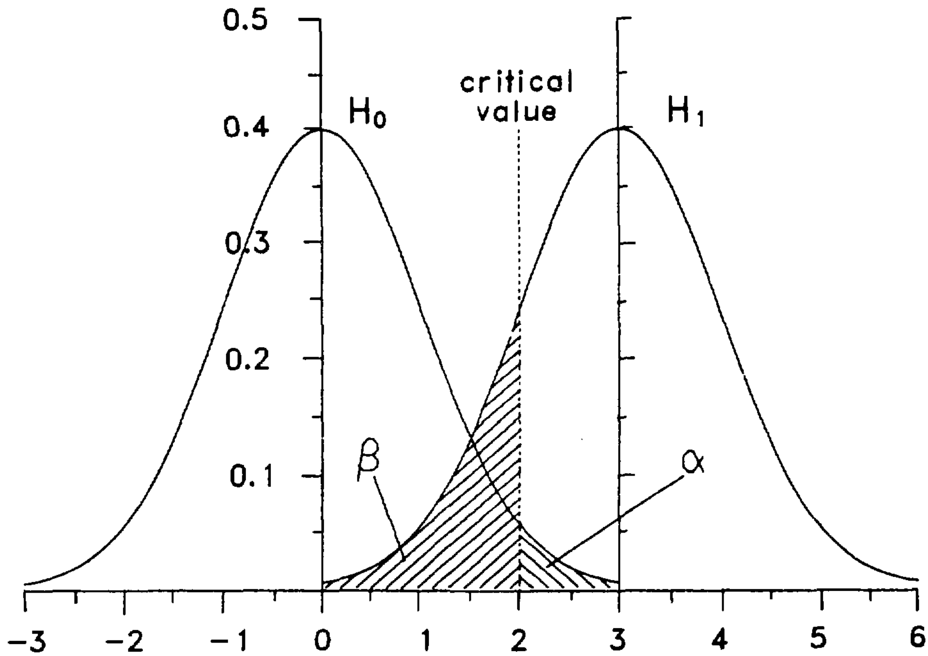

Fig. B-1. Probability density function representing no missing and missing nuclear material (in standardized units).

In this case α becomes the probability of a false alarm, that is, accepting H_1 when it is false; and $1 - \beta$ becomes the probability of detection, that is, accepting H_1 when it is true.

B. Explicit Forms of the Statistic

The ISS in the case where component falsifications of transfer and inventory measurements are considered important is called ISS_0 and is given by[1,2]

$$ISS_0 = \frac{\max[0, \bar{I}_0 - \tilde{I}_0](\bar{I}_0 - \tilde{I}_0)}{2[\bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0)]} + \frac{\max[0, \bar{I}_1 - \tilde{I}_1](\bar{I}_1 - \tilde{I}_1)}{2[\bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1)]}$$

$$+ \frac{\max[0, \bar{T}_0 - \tilde{T}_0](\bar{T}_0 - \tilde{T}_0)}{2[\bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0)]} + \frac{\max[0, \bar{T}_1 - \tilde{T}_1](\bar{T}_1 - \tilde{T}_1)}{2[\bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1)]}$$

$$+ \frac{\max[0, M_p]M_p}{2\sigma_p^2} \quad . \qquad \text{(B-1)}$$

The pooled materials balance (M_p) is a weighted sum of operator's and inspector's measurements that make up the materials balance equations, and is given by

$$M_p = \frac{\tilde{\sigma}_I^2(0)\bar{I}(0) + \bar{\sigma}_I^2(0)\tilde{I}(0)}{\bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0)} - \frac{\tilde{\sigma}_I^2(1)\bar{I}(1) + \bar{\sigma}_I^2(1)\tilde{I}(1)}{\bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1)}$$

$$+ \frac{\tilde{\sigma}_T^2(0)\bar{T}(0) + \bar{\sigma}_T^2(0)\tilde{T}(0)}{\bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0)} - \frac{\tilde{\sigma}_T^2(1)\bar{T}(1) + \bar{\sigma}_T^2(1)\tilde{T}(1)}{\bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1)} \quad .$$

The variance of M_p is

$$\sigma_p^2 = \frac{\bar{\sigma}_I^2(0)\tilde{\sigma}_I^2(0)}{\bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0)} + \frac{\bar{\sigma}_I^2(1)\tilde{\sigma}_I^2(1)}{\bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1)}$$

$$+ \frac{\bar{\sigma}_T^2(0)\tilde{\sigma}_T^2(0)}{\bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0)} + \frac{\bar{\sigma}_T^2(1)\tilde{\sigma}_T^2(1)}{\bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1)} \quad ,$$

where $\bar{\sigma}_I^2(i)$ and $\tilde{\sigma}_I^2(i)$ are the operator's and inspector's inventory measurement variances, and $\bar{\sigma}_T^2(i)$ and $\tilde{\sigma}_T^2(i)$ are the operator's and inspector's transfer measurement variances, with $i = 0,1$. The first four terms of Eq. (B-1) are sensitive to falsification of the operator's data, and the fifth term is sensitive to diversion hidden by measurement uncertainties, assuming no falsification. The ISS_0 has a chi-square distribution with five degrees of freedom.

Other forms of the ISS may be obtained, depending on the inspector's desires and the amount of information he wants to extract from the aggregate of inspector's and operator's measurements. If the inspector is not interested in identifying falsification in individual components, and is only concerned with total falsification of the materials balance, then the statistic is called ISS_1 and is written as

$$ISS_1 = \frac{1}{2}\frac{F^2}{\sigma_F^2} + \frac{M_p^2}{2\sigma_{M_p}^2} \quad , \qquad \text{(B-2)}$$

where F represents total falsification given by

$$F = (\bar{I}_0 - \tilde{I}_0) - (\bar{I}_1 - \tilde{I}_1) + (\bar{T}_0 - \tilde{T}_0) - (\bar{T}_1 - \tilde{T}_1) \quad , \qquad \text{(B-3)}$$

and σ_F^2 is the variance of F, which is given by

$$\sigma_F^2 = \bar{\sigma}_I^2(0) + \tilde{\sigma}_I^2(0) + \bar{\sigma}_I^2(1) + \tilde{\sigma}_I^2(1) + \bar{\sigma}_T^2(0) + \tilde{\sigma}_T^2(0)$$
$$+ \bar{\sigma}_T^2(1) + \tilde{\sigma}_T^2(1) \quad .$$

The ISS_1 has a chi-square distribution with two degrees of freedom.

If the inspector is not concerned with falsification and wishes to be independent of it, he should use ISS_2, which is written as

$$ISS_2 = \frac{\max\,[0, M_v] M_v}{2\sigma_v^2} \quad , \tag{B-4}$$

where M_v is the inspector's materials balance, which is

$$M_v = \tilde{I}(0) - \tilde{I}(1) + \tilde{T}(0) - \tilde{T}(1) \quad ,$$

and the variance of M_v is

$$\sigma_v^2 = \tilde{\sigma}_I^2(0) + \tilde{\sigma}_I^2(1) + \tilde{\sigma}_T^2(0) + \tilde{\sigma}_T^2(1) \quad .$$

The ISS_2 has a chi-square distribution with one degree of freedom.

Although M_p included operator's measurements, which may not have been verified, and inspector's measurements, M_v includes only those measurements that the inspector knows to be valid. If there were operator's measurements that the inspector had verified by other means, they could be included in M, with appropriate adjustment of σ^2, and would improve the sensitivity of ISS_2. Likewise, the availability of such verified operator's measurements would also improve ISS_0 and ISS_1 by allowing the removal of the corresponding terms from the falsification components.

III. USE OF THE ISS

From the above development, the inspector has at least three options for analyzing the aggregation of his own and the operator's reported data : he can use ISS_0, ISS_1, ISS_2, or combinations. The choice of the statistic has implications regarding (1) overall power of diversion detection and (2) concern with falsification.

It is generally true that, if the operator falsifies optimally, ISS_2 will have the highest detection probability of the three statistics for a specified false-alarm probability and specified level of diversion. That is, ISS_2 presumes that the operator is capable, knowledgeable, and has "done his worst." On the other hand, ISS_0 and ISS_1 generally have higher detection probabilities than ISS_2 if the operator has not falsified optimally. Optimal falsification is not trivial (see Refs. 1 and 2) and severely constrains the operator's flexibility in reporting falsified data to minimize the detection probability. ISS_1 represents a compromise between the characteristics of ISS_0 and ISS_2.

Thus, each of the three statistics has certain advantages that can only be evaluated through careful consideration of the compromises between detection probability and limitation on divertor flexibility. In the following sections, we examine the characteristics of the three statistics, beginning with the simplest, ISS_2.

A. No Data Falsification - ISS_2

The statistic given by Eq. (B-4) considers the inspector has interest only in detecting diversion. The test statistic is distributed as chi-square with one degree of freedom. In Eq. (B-4) M_v is negative; we set it equal to zero and accept H_0 that there is no diversion. This implies that we are interested in a one-sided test; a two-sided test would add little to the development. Let us now formally state our hypothesis and calculate the rejection region and the power of the test for various alternative hypotheses. We assume that the expected value of the materials balance is represented by μ. The hypotheses can be written as

$$H_0 : \mu = 0$$

$$H_1 : \mu > 0 \quad .$$

For a one-sided test with a false-alarm probability equal to α, we multiply α by two and select the corresponding critical value from the chi-square tables under one degree of freedom. For $\alpha = 0.05$, the critical region is where the test statistic exceeds 1/2(2.71). Thus, when $ISS_2 > 1.35$, we accept H_1.

To calculate the power of this test, we must specify the alternative hypothesis, that is,

$H_0: \mu = 0$

$H_1: \mu = d$.

We have opted to use the simple notation d to represent the more commonly preferred terminology μ_d. The power calculation requires the use of a noncentral chi-square distribution depending on the particular alternative hypothesis. The term noncentral is used for chi-square distributions where the independent normal random variables have a common variance but do not have zero means. Therefore, the detection probability for the related sufficient statistics requires the use of the noncentral chi-square distribution for the alternative hypotheses. The noncentral chi-square distribution is characterized by (1) the noncentrality parameter λ, and (2) the degrees of freedom.

The power of the test, or detection probability, for $\alpha = 0.05$ and $d = 1.0\sigma_v$ is 0.26. Here d is a particular value of diversion. To calculate the power, let $\lambda = d^2/\sigma_v^2$ and enter a noncentral chi-square table that gives the power for 2α and one degree of freedom.[3]

B. Pooled Data Falsification - ISS_1

Because we want to perform a one-sided test, it is necessary to modify observations of F and M_p that are negative so that they do not result in a test statistic value that causes acceptance of H_1 when it is false. In this situation (under H_0), the test statistic is composed of two independent chi-square variables each with one degree of freedom. Thus, the test statistic is a chi-square variable with two degrees of freedom. In the modified procedure we replace any negative values of F and M_p from Eqs. (B-2) and (B-3) by zero. This procedure results in the modified test statistic (see Ref. 2)

$$ISS_1 = \begin{cases} 0 & , \quad F \leq 0 \ , \quad M_p \leq 0 \ , \\ \dfrac{F^2}{4\sigma^2} & , \quad 0 < F \ , \quad M_p \leq 0 \ , \\ \dfrac{M_p^2}{\sigma^2} & , \quad F \leq 0 \ , \quad 0 < M_p \ , \\ \dfrac{F^2}{4\sigma^2} + \dfrac{M_p^2}{\sigma^2} & , \quad 0 < F \ , \quad 0 < M_p \ , \end{cases}$$

where we have chosen the variance of the operator's or inspector's materials balance to be equal to σ^2. We require the critical region of the test and the power of the test for various alternative hypotheses.

1. Determine the Critical Regions. The null hypothesis is

$$H_0 : \mu_d = 0 \text{ and } \mu_f = 0 \quad ,$$

where μ_d and μ_f are the expected values of M_p and F, respectively. We define

$$u = \frac{F}{\sigma\sqrt{2}} \quad , \quad v = \frac{\sqrt{2}M_p}{\sigma} \quad ,$$

which are both unit normal random variables with $\mu_u = \partial_f$ and $\mu_v = 2\mu_d - \mu_f$. The distribution under H_0 may be divided into four regions and is given by

(1) $u < 0,\ v < 0$ $\qquad f(u, v) = {}_4, \quad u = v = 0$

(2) $u < 0,\ 0 < v$ $\qquad f(u, v) = \frac{1}{2}\frac{1}{\sqrt{2\pi}} e^{-v^2/2}, \quad u = 0,\ 0 < v < \infty$

(3) $0 < u,\ v < 0$ $\qquad f(u, v) = \frac{1}{2}\frac{1}{\sqrt{2\pi}} e^{-u^2/2}, \quad v = 0,\ 0 < u < \infty$

(4) $0 < u,\ 0 < v$ $\qquad f(u, v) = \frac{1}{2\pi} e^{-(u^2+v^2)/2}, \quad 0 < u,\ v < \infty$.

Region 1. There is no interest in this case because H_0 will always be accepted.

Region 2, One Degree of Freedom. Along the v axis the critical region is found by solving for x_1, given by

$$\frac{1}{2}\frac{1}{\sqrt{2\pi}}\int_{x_1}^{\infty} e^{-v^2/2}\, dv = c_1\alpha \quad , \tag{B-5}$$

where α is the false-alarm probability and c_1 is a constant. The factor 1/2 in Eq. (B-5) is necessary because the negative half plane ($v < 0$) was excluded.

Region 3, One Degree of Freedom. Along the u axis the critical region is found by solving for x_2, given by

$$\frac{1}{2}\frac{1}{\sqrt{2\pi}}\int_{x_2}^{\infty} e^{-u^2/2}\, du = c_2\alpha \quad , \tag{B-6}$$

where α is defined in Eq. (B-5) and c_2 is a constant. The factor 1/2 in Eq. (B-6) is required for a reason similar to that given above.

Region 4, Two Degrees of Freedom. In the first quadrant, a standard type of transformation[4,5] facilitates the determination of the critical region. Let $w = u^2 + v^2$ and $z = u^2$ with $0 < z < w$. This produces a joint density function

$$g(w, z) = f(u, v)\,|j| = \frac{e^{-w/2}}{8\pi\sqrt{zw - z^2}} \quad ,$$

where $|J|$ is the absolute value of the Jacobian.

The joint density function of the random variables w and z is integrated with respect to z, producing the density function

$$g(w) = \frac{1}{8\pi}\int_0^w \frac{e^{-w/2}}{\sqrt{zw - z}}\, dz = \frac{e^{-w/2}}{8} \quad .$$

Note that g(w) is 0.25 times the chi-square probability density function with two degrees of freedom.

The critical region is found by solving for x_3, given by

$$\frac{1}{8} \int_{x_3}^{\infty} e^{-w/2} \, dw = \frac{e^{-x_3/2}}{4} = c_3\alpha \quad . \qquad \text{(B-7)}$$

$$x_3 = -2 \ln (4c_3\alpha) \quad .$$

The restrictions on the c's are

$$c_1 + c_2 + c_3 = 1 \quad \text{and} \quad 0 < c_i < 1 \quad \text{for } i = 1, 2, 3 \quad .$$

An example of the critical region is given by $x_1 = x_2 = \sqrt{x_3}$; that is, only one critical value. The appropriate value is obtained by solving

$$\frac{1}{\sqrt{2\pi}} \int_{\sqrt{x_3}}^{\infty} e^{-t^2/2} \, dt + \frac{e^{-x_3/2}}{4} = \alpha \quad . \qquad \text{(B-8)}$$

Equation (B-8) is the sum of Eqs. (B-5), (B-6), and (B-7). When $\alpha = 0.05$, x_1 and $x_2 \sim 2.06$, and $x_3 = 4.23$. This scheme allocates three times as much of α to the first quadrant as it allocates to each axis.

2. Determine the Power of the Test. The alternative hypothesis is composed of three parts and is

$$H_1: \quad \mu_f > 0 \quad , \quad \mu_d = 0 \quad ,$$

$$\mu_d > 0 \quad , \quad \mu_f = 0 \quad ,$$

$$\mu_f > 0 \quad , \quad \mu_d > 0 \quad .$$

Now u and v are independent, normal random variables with unit variance and means $\mu_f/\sigma\sqrt{2}$ and $\mu_d\sqrt{2}/\sigma$, respectively.

Region 1. Region 1 does not contribute to the power of the test because both u and v are negative.

Region 2. $u < 0$, $v > 0$. Here u is set equal to 0, which corresonds to $\mu_d = 0$, $\mu_f > 0$. Let $h_1(1 - \beta)$ represent the power contributed by the v axis,

$$h_1(1 - \beta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{0} e^{-(u-\mu_u)^2/2}\, du \frac{1}{\sqrt{2\pi}} \int_{x_1}^{\infty} e^{-(v-\mu_v)^2/2}\, dv$$

$$h_1(1 - \beta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mu_u} e^{-t^2/2}\, dt \frac{1}{\sqrt{2\pi}} \int_{x_1-m_v}^{\infty} e^{-t^2/2}\, dt \quad .$$

Region 3. $u > 0$, $v < 0$. Here v is set equal to 0, which corresponds to $\mu_d > 0$, $\mu_f = 0$. The power contributed by the u axis is

$$h_2(1 - \beta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mu_v} e^{-t^2/2}\, dt \frac{1}{\sqrt{2\pi}} \int_{x_2-\mu_u}^{\infty} e^{-t^2/2}\, dt \quad .$$

Region 4. $u > 0$, $v > 0$. This case corresponds to $\mu_f > 0$ and $\mu_d > 0$. The power contributed by this region is

$$h_3(1 - \beta) = \frac{1}{2\pi} \int_{v=0}^{\infty} \int_{u=\sqrt{x_3-v^2}}^{\infty} \exp\left[\frac{(u - m_u)^2 + (v - u_v)^2}{2}\right] du\, dv \ .$$

Calculation of $h_1(1 - \beta)$ and $h_2(1 - \beta)$ is more accurate than $h_3(1 - \beta)$ because they are single integrals. Numerical integration of a double integral is necessary to estimate $h_3(1 - \beta)$.

The total power is given by

$$P = h_1(1 - \beta) + h_2(1 - \beta) + h_3(1 - \beta) \quad .$$

When $x_1 = x_2 = x$, the power is

$$P = 2\Phi(-\mu_u)\Phi(\mu_u - x)$$

$$+ \frac{1}{2\pi} \int_{v=0}^{\infty} \int_{u=\sqrt{x_3 - v^2}}^{\infty} \exp\left[\frac{(u - \mu_u)^2 + (v - \mu_v)^2}{2}\right] du\, dv \quad , \tag{B-9}$$

where

$$x_3 = -2 \ln \{4[\alpha - \Phi(-x)]\} \quad , \text{ and}$$

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-t^2/2}\, dt \quad .$$

The detection probability, or power, is 0.23 for $\mu_d = \mu_f = 1\sigma$ with equal critical values, $x_1 = x_2 = x_3$, and a false-alarm probability equal to 0.05.

The critical values given above were determined by numerical integration and checked by Monte Carlo simulation; they were selected to achieve the desired value of $\alpha = 0.05$. Likewise, the power of test, for either set of critical values, was determined by numerical integration and checked by Monte Carlo simulation for various values of diversion and falsification. It was also shown that the minimum power is attained for each case when diversion equals falsification.

When maximum power is attained, nearly all of it is contributed by h_3. That is, h_1 and h_2 are essentially disregarded, and we are concerned with both positive diversion and positive falsification. An alternative procedure, which when tested produced the same power to two decimal places as the maximizing procedure, would consider only h_3. The difference between the maximum power and the power when $x_1 = x_2 = x_3$ is small so that the latter procedure is close to optimal and is operationally feasible.

C. Falsification of Data by Components - ISS_0

The case of eight measured quantities, four by the operator and four by the inspector, will now be considered. A more rigorous and detailed treatment of this problem is found in Ref. 2. The following account uses a different approach to arrive at results presented in Ref. 2. Notation is changed to help make this special setting of the model more readily understood by the uninitiated reader. In addition, the likelihood ratio technique of Ref. 2 is replaced by formulating the model, solving for the estimates, and using equations from Ref. 2 in the development to obtain critical regions and power curves.

1. Notation and Model. The notation for this discussion is

- o - operator;
- i - inspector;
- b - beginning of a materials balance period or input to a materials balance area;
- e - ending of a materials balance period or output from a materials balance area;
- I - measured inventory, for example, I(o,b) represents the operator's measured value of initial inventory;
- T - measured transfer, for example, T(i,e) represents the inspector's measurement of material transferred out of the process;
- ξ - the true value of an inventory, for example, $\xi(e)$ represents the unknown precise value of ending inventory;
- τ - the true value of a transfer;
- γ - the true value of falsification, for example, $\gamma_I(b)$ represents the unknown value (to the inspector) by which the operator has falsified his reports on the beginning inventory;
- ε - a random error, normal, identically independently distributed with mean 0 and variance σ_ε^2;
- δ - the unknown value of the amount of diversion;
- d - an estimator of δ;

f - an estimator of γ, for example, $f_T(e)$ is the amount of falsification estimated for T(o,e) and estimates the true value $\gamma_T(e)$; and

F - total falsification.

The general linear model may be formulated

$$I(o,b) = \xi(b) + \gamma_I(b) + \varepsilon_I(o,b) \quad ,$$

$$I(o,e) = \xi(e) + \gamma_I(e) + \varepsilon_I(o,e) \quad ,$$

$$I(i,b) = \xi(b) + \varepsilon_I(i,b) \quad ,$$

$$I(i,e) = \xi(e) + \varepsilon_I(i,e) \quad ,$$

$$T(o,b) = \tau(b) + \gamma_T(b) + \varepsilon_T(o,b) \quad ,$$

$$T(o,e) = \tau(e) + \gamma_T(e) + \varepsilon_T(o,e) \quad ,$$

$$T(i,b) = \tau(b) + \varepsilon_T(i,b) \quad , \text{ and}$$

$$T(i,e) = \tau(e) + \varepsilon_T(i,e) \quad .$$

2. Finding Estimates of Falsification and Diversion. The problem is to find estimates of ξ, τ, γ, and $\delta = \xi(b)\ \xi(e) + \tau(b) - \tau(e)$. Each of the I and T variables are normally distributed and that variances can be readily identified using the above notation [for example, $\sigma_I^2(o,b)$ is the variance of I(o,b), etc.]. The solutions for falsification f (estimates of γ) are readily obtained by letting 0 be the estimate for each ε. Then,

$$f_I(b) = I(o,b) - I(i,b) \quad ,$$

$$f_I(e) = I(o,e) - I(i,e) \quad ,$$

$$f_T(b) = T(o,b) - T(i,b) \quad , \text{ and}$$

$$f_T(e) = T(o,e) - T(i,e) \quad .$$

Assuming that the inspector and operator make corresponding measurements equally well, the estimates for the inventories and transfers, if falsification may have occurred, are

$$\hat{\xi}(b) = \frac{1}{2}[I(o,b) - f_I(b) + I(i,b)] = I(i,b) \quad ,$$

$$\hat{\xi}(e) = I(i,e) \quad ,$$

$$\hat{\tau}(b) = T(i,b) \quad , \text{ and}$$

$$\hat{\tau}(e) = T(i,e) .$$

The estimator of diversion is given by

$$d = I(i,b) - I(i,e) + T(i,b) - T(i,e) \quad ,$$

and, as expected, the estimate of diversion when falsification takes place is a function of the inspector's measurements alone. If the inspector assumes that no falsification has taken place but wishes to estimate diversion, δ may be estimated by using

$$d = \frac{1}{2}[I(o,b) - I(o,e) + T(o,b) - T(o,e) + I(i,b) - I(i,e) + T(i,b) - T(i,e)] \quad .$$

We have found a set of normally distributed variables with known variances. The quantity designated by ISS_0 in Eq. (B-1) can be expressed as a sum of independent central chi-square variables under the null hypothesis of zero means,

$$\chi^2 = \frac{f_I(b)^2}{2\sigma_{I0}^2} + \frac{f_I(e)^2}{2\sigma_{I1}^2} + \frac{f_T(b)^2}{2\sigma^2_{T0}} + \frac{f_T(e)^2}{2\sigma_{T1}^2} + \frac{(2\mu_d - \mu_f)^2}{2(\sigma_{I0}^2 + \sigma_{I1}^2 + \sigma_{T0}^2 + \sigma_{T1}^2)}$$

$$= u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2 \quad ,$$

which has five degrees of freedom, and $F = f_I(b) - f_I(e) + f_T(b) - f_T(e)$. We have assumed that the inspector and the operator have equal variances in their measurements, or that

$$\sigma^2_{I0} = \sigma^2_I(o,b) = \sigma^2_I(i,b) \quad ; \quad \sigma^2_{I1} = \sigma^2_I(o,e) = \sigma^2_I(i,e) \quad ,$$

$$\sigma^2_{T0} = \sigma^2_T(o,b) = \sigma^2_T(i,b) \quad ; \quad \text{and } \sigma^2_{T1} = \sigma^2_T(o,e) = \sigma^2_T(i,e) \quad .$$

Each term can be used as a separate test, and if $F = d$, then each term would test falsification and diversion in respective order.

3. Finding Critical Regions. There are 31 critical regions that can be classed in 5 groups having different characteristics found under

H_0: $\gamma_I(b) = \gamma_I(e) = \gamma_T(b) = \gamma_T(e) = \delta = 0$ versus

H_1: at least one parameter in H_0 not 0.

Note that u_i, $i = 1, 2, 3, 4, 5$ as defined in the chi-square breakdown is a standardized, normal variable and $-\infty < u_i < \infty$. If all realized $u_i \leq 0$, the hypothesis is automatically accepted and values of γ and δ may be considered equal to 0. For H_0 true, the probability that any one $u_i < 0$ is equal to 1/2; therefore the chance of all five estimates being negative is 1/32. The other five regions where the hypothesis can be rejected are examined below.

Region 1, One Degree of Freedom. There are four variables whose realizations are 0 and one whose realization is a positive quantity. Find a value of x_1 that satisfies

$$\left(\tfrac{1}{2}\right)^4 \frac{1}{\sqrt{2\pi}} \int_{\sqrt{x_1}}^{\infty} e^{-t^2/2}\, dt = c_1\alpha \quad ,$$

where c_1 is a positive constant similar to the c's defined in Sec. C.2.a above. There are five possibilities of this event occurring.

Region 2, Two Degrees of Freedom. There are three variables whose realizations are 0 and two whose realizations are positive quantities. Find a value of x_2 such that

$$\left(\frac{1}{2}\right)^3 \frac{1}{4} \int_{x_2}^{\infty} f(\chi^2;2) = c_2\alpha \quad ,$$

where the integral is the chi-square distribution with two degrees of freedom. There are 10 possibilities where any 2 of the 5 variables are positive.

Region 3, Three Degrees of Freedom. Two variables whose realizations are 0 and three whose realizations are positive values give rise to an x_3 such that

$$\left(\frac{1}{2}\right)^2 \frac{1}{8} \int_{x_3}^{\infty} f(\chi^2;3) = c_3\alpha \quad .$$

The integral is the chi-square distribution with three degrees of freedom. There are 10 such regions.

Region 4, Four Degrees of Freedom. One variable whose realization is 0 and four whose realizations are positive values require an x_4 such that

$$\left(\frac{1}{2}\right)\left(\frac{1}{16}\right) \int_{x_4}^{\infty} f(\chi^2;4) = c_4\alpha \quad .$$

The integral is the chi-square distribution with four degrees of freedom. There are five such regions.

Region 5, Five Degrees of Freedom. All variables take on positive values. Find x_5 such that

$$\frac{1}{32}\int_{x_5}^{\infty} f(\chi^2;5) = c_5\alpha \quad .$$

The integral is the chi-square distribution with five degrees of freedom.

In all regions, α specifies the size of the rejection area and $5c_1 + 10c_2 + 10c_3 + 5c_4 + c_5 = 1$. When $\alpha = 0.05$, and all the x_i's are equal, we find the values of the x_i's ~ 7.48.

4. Determine the Power of the Test. The power function is obtained by examining the probability of rejecting the alternative hypothesis. Terms for each integral under the null hypothesis are now replaced in the following manner (μ_{u_j} denotes the value given to the mean of u_j):

Under H_0	Under H_1
$\frac{1}{\sqrt{2\rho}}\int_{x}^{\infty} e^{-t^2/2}\,dt$	$\frac{1}{\sqrt{2\rho}}\int_{x-\mu_{u_j}}^{\infty} e^{-t^2/2}\,dt$
$f(\chi^2;df)$	$f(\chi'^2;df,\lambda)$

where $f(\chi^2;df)$ is a chi-square distribution, and $f(\chi'^2;df,\lambda)$ is a noncentral chi-square distribution with $\lambda = \Sigma(\mu_{u_j}^2/\sigma_{u_j}^2)$.

The total power is equal to the sum of the individual contributions and is similar to Eq. (B-9), but for ISS_0 there are 31 individual critical regions. If we assume that all similar cases (regions) will have identical critical values, the problem simplifies to five different regions.

IV. COMPARING THE THREE STATISTICS

Figure B-2 shows power curves for ISS_0, ISS_1, and ISS_2 as functions of the diversion d for optimal falsification in each case. The operator's or inspector's materials balance standard deviations are assumed to be equal to σ; consequently, the diversion d is chosen as a multiple of σ. The curves were obtained by numerical integration with appropriate,

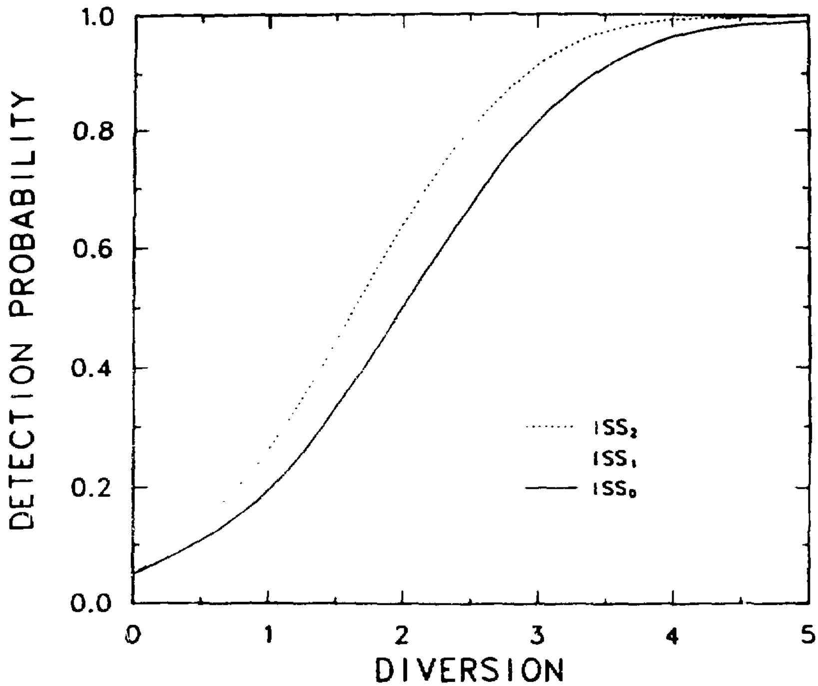

Fig. B-2. Power curves for ISS_0, ISS_1, and ISS_2; optimal falsification and 0.05 false-alarm probability.

equal critical values for each statistic, and a false-alarm probability of 0.05. The numerical solutions were checked by simulations. Randomly generated samples from a normal distribution were used to compute the power for various diversion and falsification amounts. Typically 20 000 to 50 000 random samples were used to obtain sufficient statistics. The results of the numerical integrations and the simulations were in good agreement.

The results show that ISS_2, the statistic that is independent of operator's measurement falsification, has the highest detection probability; whereas ISS_0, which is sensitive to component falsification, has the lowest for optimal falsification; and ISS_1 has intermediate detection probability. However, the differences are not great; at a diversion d of twice the inspector's materials balance standard deviation, the detection probabilities are approximately 0.50, 0.57, and 0.64 for ISS_0, ISS_1, ISS_2, respectively. At d equals three times the inspector's materials balance standard deviation, the respective detection probabilities are about 0.81, 0.87, and 0.91.

In addition, the inspector's use of ISS_0 severely limits the operator's flexibility in falsifying data to hide diversion. If the operator does not falsify properly, the detection probabilities for ISS_0 and ISS_1 increase, whereas that for ISS_2 remains the same. In particular, Fig. B-3 shows power curves for ISS_0, ISS_1, and ISS_2 in the case of no falsification at all. Now, ISS_1 is uniformly better than ISS_2, whereas ISS_0 is better than ISS_2 for diversion larger than ∿ 1.6. These results show that the three statistics are similar in performance, but it appears that ISS_1, which tests for diversion and/or total materials balance falsification, is an effective compromise.

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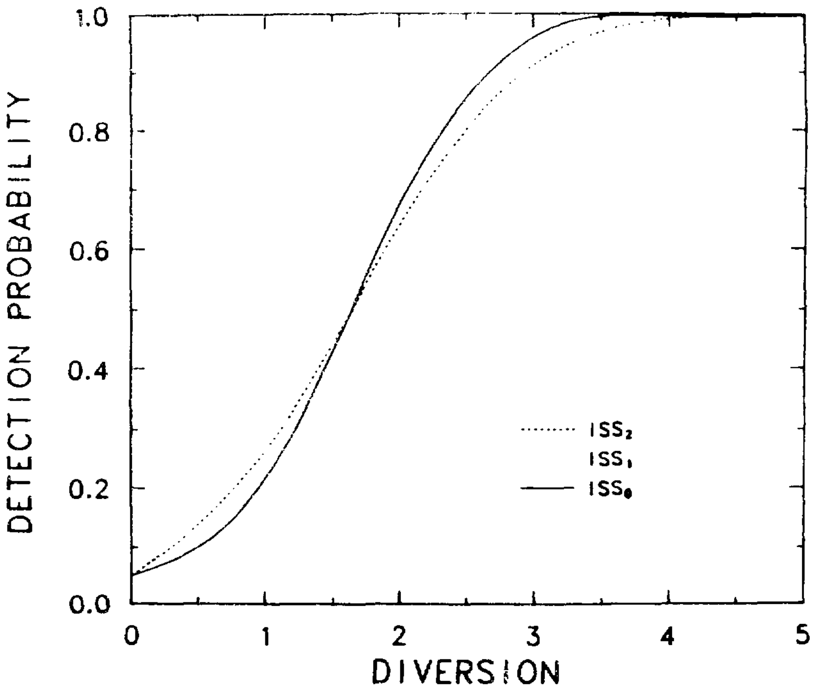

Fig. B-3. Power curves for ISS_0, ISS_1, and ISS_2; no falsification and 0.05 false-alarm probability.

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APPENDIX C

QUANTIFYING PERFORMANCE OF PENETRATION-MONITORING SYSTEMS

by
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I. SYSTEMS PERFORMANCE

Systems performance may be characterized by the probability P(d) that at least one indication of an amount of material being removed through an instrumented penetration is received in the course of removal over a fixed time period T. The systems probability of detecting a particular means or strategy for diverting a specified amount of material may be calculated if the individual sensor detection functions are known and if certain assumptions regarding statistical independence are made. There may, however, be numerous possible diversion strategies involving the use of the various instrumented penetrations, and each may result in a different value of detection probability. Therefore, what strategy should be used to characterize system performance? Because a potential divertor may be aware of the detection sensitivities of the various systems components, it is reasonable to assume that he would choose the strategy that minimizes the system probability of detection P(d). This strategy is referred to as the worst-case diversion strategy.

A. Formulation of the Evaluation Problem

An important part of the evaluation problem is efficient identification of the worst-case diversion strategy. In general it will be desirable to determine systems performance for a range of diversion amounts and a number of time periods. This requires identifying many worst-case diversion strategies because a different strategy may be worst-case for each diversion amount and time period. A method for identifying worst-case diversion strategies and for evaluating systems performance was developed, based upon dynamic programming techniques, and is described in this appendix.

As a convenient means of visualizing the problem, a system of penetrations of containment boundaries is modeled as a network, which is a collection of nodes joined by arcs. For this problem, the area of a facility within each containment boundary is represented by a node. Figure C-1 shows an example network for a facility that includes two containment boundaries. The node labeled "primary containment zone" refers to an

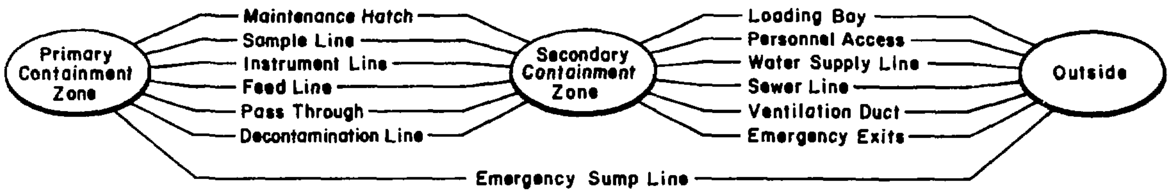

Fig. C-1. Diversion flow network.

area within the inner (primary) containment boundary, and the node labeled "secondary containment zone" refers to the area between the inner (primary) and outer (secondary) containment boundaries. The node labeled "outside" refers to all areas located outside of any containment barrier. The arcs between two nodes represent the penetrations through the containment boundary that separates the zones.

A diversion would require material moving from the primary containment zone to the outside. As shown in Fig. C-1, many possible combinations of penetrations may be used for diverting material, and thus, there are many possible diversion strategies. This is especially the case when the possibility of simultaneous diversion through a number of penetrations is considered. In addition, the temporal features of a diversion strategy may affect the overall probability of detection. As discussed in Sec. V.B, the detection probability for a surveillance device is stated with respect to movement of an amount m during a fixed time interval. The system can be evaluated with respect to a period of time that covers many of the specified sensor time intervals. For example, a time interval for a portal would be the transit time for one pass through the portal. The total number of active time intervals that could be used in a diversion strategy would be the allowed number of transits during the system evaluation period. For a piping radiation monitor, a time interval would be a counting time, and the time interval for a seal would be the time during which it is applied. Detection probability for one strategy involving diversion of a particular amount past a sensor in one time interval could be different from that for a strategy involving diversion of the same amount, divided into several portions over several time intervals. Thus, the set of potential strategies that must be considered in the identification of worst-case diversion strategies derives from temporal as well as spatial considerations. Each arc of the network must be replicated for as many time intervals as may occur for the associated sensor during the systems evaluation period.

B. Solving the Evaluation Problem

In the evaluation procedure, the detection probability for a surveillance device is described as a function of the amount of material diverted during a particular time interval. These data must be available as input for the evaluation; however, the data do not have to be described by a mathematical expression, but may be in the form of discrete points based upon empirical or analytical evaluation of a device. In all cases, when used as input to the particular evaluation methods described here, the data will be approximated by a series of discrete points.

Two assumptions apply to the manner in which the data are combined in performing the analysis. First, the probability of detection associated with any one arc in the network must be treated as independent of all other arcs. In other words, in this method the detection probability of diversion arising from a particular time interval for a particular sensor is considered to be independent of the detection probability of diversion for any other time interval or any other sensor. In this method only, therefore, two considerations are eliminated: (1) sources of correlated measurement error, such as calibration error, and (2) the accumulation of measurement data over several time intervals before a decision of detection or nondetection of material movement is made.

Second, the probability of detection for a surveillance device is taken to be zero when no material moves past that device during the associated time interval. In other words, no credit for detection is given to one sensor if there is an unrelated (false) alarm from another sensor in the system. Unlike the first assumption, this latter assumption is not a requirement of the mathematical model.

The procedure for identifying worst-case diversion strategies and evaluating systems performance involves considering groups of parallel and groups of series arcs. When groups of parallel arcs are considered, the problem is to

$$\text{maximize} \quad \prod_{i=1}^{n} [1 - p_i(m_i)] = \prod_{i=1}^{n} \bar{p}_i(m_i) \tag{C-1}$$

$$\text{subject to the constraint} \quad \sum_{i=1}^{n} m_i = d \quad , \text{ and}$$

$$m_i > 0 \quad , \quad \text{for all } i \quad ,$$

where $\bar{p}_i$ (= 1 - p_i) is called the detection avoidance function.

This mathematical formulation represents a determination of a diversion strategy $m_1, m_2, ..., m_n$, where an m_i is associated with each of the n arcs in the network, so that the composite probability of avoiding detection for diversion of the total amount d through the group of parallel arcs is also maximized. By solving the maximization problem defined in Eq. (C-1) for different values of d, a composite probability of detection function for an entire set of parallel instrumented penetrations can be constructed.

The network representation of an actual facility may include penetrations in series as well as in parallel. For example, the network shown in Fig. C-1 represents a hypothetical facility with penetrations between the primary containment zone (P) and the secondary containment zone (S), between S and the outside (O), and also directly between P and O.

This network can be analyzed for a specific time period by decomposing it into four steps involving repeated solution of the minimization problem for the various parts of the network as follows.

(1) Solve the maximization problem given in Eq. (C-1) for the arcs from P to S for all diversion amounts of interest, obtaining a composite detection avoidance function.

(2) Solve the maximization problem given in Eq. (C-1) for the arcs from S to O for all diversion amounts of interest, obtaining a composite detection avoidance function.

(3) Form a detection avoidance function, P_3, for the series system, P to S to O, by taking the product of the composite detection avoidance functions from steps 1 and 2, P_1 and P_2, as follows:

$$\bar{P}_3(d) = \bar{P}_1(d) \cdot \bar{P}_2(d) \quad .$$

(4) Solve the maximization problem to obtain a single equivalent network of detection avoidance function by using the function from step 3 in parallel with the arcs directly from P to O.

The composite function that results from step 4 is the probability detection avoidance function for the diversion amounts of interest for the specified period of time. The system probability of detection [called $P(d,\underset{\sim}{m}^*)$ in Sec. V.B.1] is then obtained by subtracting this detection avoidance function from unity.

The practicality of this decomposition approach depends on being able to solve the maximization problem defined by Eq. (C-1) for all diversion amounts d in an efficient manner. Dynamic programming[1-3] can be used to solve the maximization problem defined by Eq. (C-1). Like other methods (such as those using gradient algorithms), it does not require the examination of every possible diversion strategy to determine the optimal one. However, unlike gradient methods, it is guaranteed to find the optimal strategy, and, once the problem is solved for a particular value of d, solutions for lower values are simultaneously provided.

The basic observation underlying dynamic programming is the principle of optimality that allows us to break a complex problem into subproblems. The principle of optimality applied to this problem can be stated as: From any point in an optimal diversion strategy, the remaining diversion is optimal for the corresponding problem initiated at that point. Thus, if an optimal strategy for the network of Fig. C-1 is being considered, and it is known that as part of this strategy some amount of material will be diverted across certain arcs, the diversion of any remaining amount over the remaining arcs will also be optimal when viewed by itself.

The principle of optimality allows the problem to be viewed as a sequence of decisions to be made, and thus an optimal diversion strategy may be built up by working backwards. The divertor must decide how much to divert through arc n, how much through arc (n - 1), etc. Moving backward from arc n, a composite probability of avoiding detection is calculated recursively. If the decision for arc n (the last decision) is about to be made with k units left to allocate out of an original d units to be diverted, the decision is easy: all k units are allocated to arc n. If V_i denotes the composite detection avoidance function for optimal allocation decisions associated with arcs i, ..., n, the decision for the arc n is

$$V_n(k) = \bar{p}_n(k) \quad \text{and} \quad k = 0, 1, \ldots, u_n \quad .$$

That is, the composite detection avoidance function at arc n is simply the individual detection avoidance function for arc n evaluated at k. All possibilities for the number of units left to allocate are considered by letting k vary between 0 and u_n, where u_i is a value such that $\bar{p}_i(x)$ is essentially equal to zero for $x > u_i$.

When k units remain at the step (n - 1), these units must be split between penetrations (n - 1) and n. The composite detection avoidance function at arc (n - 1) is found by taking the product of the composite function at arc n and the individual detection avoidance function for arc (n - 1) for all possible splits of k. The split that produces the maximum composite function is the one retained for use in consideration of subsequent arcs. Mathematically, this is

$$V_{n-1}(k) = \sum \max \left[\bar{p}_{n-1}(x) * V_n(k - x)\right] \quad , \quad k = 0, \ldots, u_{n-1} + u_n \quad ,$$

$$0 \leq x \leq u_{n-1}$$

$$0 \leq k - x \leq u_n \ .$$

In general,

$$V_i(k) = \sum \max \left[\bar{p}_i(x) * V_{i+1}(k - x)\right] \quad , \quad k = 0, 1, \ldots, \sum_{j=i}^{n} u_j \quad ,$$

$$0 \leq x \leq u_i$$

$$0 \leq k - x \leq \sum_{j=i+1}^{n} u_j \ .$$

The function V_1 is then the detection avoidance function for the entire system. By saving the optimal x's at each step for each k, the optimal diversion strategies can be recovered.

The individual detection avoidance functions $\bar{p}_i$ must be step functions with steps at integer values for this procedure to work. However, this should not be a severe restriction in practice because an arbitrary number of steps can be used to describe any particular detection avoidance function. In fact, for complex instrumentation where the theoretical form of the detection avoidance function is not well understood, a few experimentally obtained data points may have to suffice for the characterization of instrument performance. The solution method outlined here is suitable for any form of function as long as the step-function restriction is met.

The dynamic programming methodology has flexibility in accepting essentially any form of input. It guarantees global optima and provides solutions for all discrete values of d by solving the problem once. Another attractive feature of the dynamic programming approach is that it should be possible to carry out sensitivity analyses efficiently. In this regard, it is important to recognize that, although efficient heuristic or approximate solution methods could be developed, their weakness is in the difficulty of indicating how far the best solution is from the optimum. This causes problems in sensitivity analysis; with an approximate solution method, a change in the solution, which might occur when an input parameter is altered, could be brought about by a shift in the accuracy of the approximate solution (that is, through luck) instead of by the parameter change.

C. Computational Efficiency of Dynamic Programming

An important consideration in the development of a solution methodology for any problem is the computational effort required. Equation (C-1) can be solved with dynamic programming for all diversion amounts d at the same time. Obviously, for discrete problems, exhaustive enumeration is always a possible approach; however, this can be a very expensive procedure. The solution of Eq. (C-1) using complete enumeration would require

$$\prod_{i=1}^{n-1} (u_i + 1)$$

multiplications, and that would be a prohibitive task even for moderate size n and u_i. It can be shown that the dynamic programming algorithm described above requires no more than

$$\sum_{i=1}^{n-1} (u_i + 1)[1 = \max (u_i, \sum_{j-i+1}^{n} u_j)]$$

multiplications. In fact, the number of multiplications increases only quadratically (not exponentially) as n or the u_i's increase. This represents a significant savings over complete enumeration. For example, if $u_i = u$ for all i, complete enumeration would require $(u + 1)^{n-1}$ multiplications compared to n^2u^2 (approximately) operations for the dynamic programming algorithm.[3]

In considering expansion of networks both in space and time, it is apparent that the number of arcs in a network may be quite large. The number of operations required in solving a dynamic programming problem is roughly proportional to the square of the number of arcs; thus, it is better to reduce the problem, if possible, before applying the dynamic programming method. In the absence of consideration of phenomena that introduce time dependence, such as reliability, all arcs representing the various time intervals for an instrumented penetration will be identical. In addition, arcs representing similar instruments on similar penetrations may also be essentially identical. It can be shown that if the logarithm of the function $[1 - p_i(m)]$ for a particular arc is everywhere concave, the composite arc representing a group of identical arcs may easily be generated. Further, it is shown that if an amount d is to be diverted through n identical, parallel arcs, a strategy that will minimize the probability of detecting diversion of the amount d will be to divert equal amounts d/k across k of the arcs, and no material across the remaining n - k arcs. In practice, most, if not all, detection functions exhibit the log concave property, and significant reduction of the computational effect for the dynamic programming method may be achieved by application of this technique. Therefore, the capability to apply this technique was incorporated as part of the algorithm for penetration-monitoring systems evaluation.

D. False Alarms, Reliability, and Systematic Error

In addition to the systems probability of detection, false-alarm probability is also an important measure of systems performance. If a false-alarm probability (f_i) is associated with each arc in a network, that is, with each time interval for each surveillance device, the system's false-alarm probability for the period of time represented by the network is

$$1 - \prod_i (1 - f_i) \quad .$$

This is the probability that, in the absence of diversion, an alarm will be generated by at least one surveillance device during the period of time specified. The expected number of false alarms in the specified period of time is a complementary figure expressed by

$$N_f = \sum_i f_i \quad .$$

The possibility of instrument failure introduces a complicating factor into the analysis. An unreliable instrument will raise the detection avoidance function for all values of alarm threshold and diversion concentrations. The amount with which the detection avoidance probability is increased depends upon the failure rate of the instrument and the time elapsed since it was last determined to be functioning.

As in the previous section, let time be indexed for a particular instrument in terms of the number of elapsed counting intervals. The probability of detecting a diversion that takes place in counting interval t is simply the probability of detecting the diversion, assuming that the instrument is operating, multiplied by the probability that the instrument is operating. This can be expressed as

$$p(m)(1 - \lambda)_t \quad ,$$

where p(m) is the detection probability, assuming that the instrument is operating properly.

To take advantage of possible instrument failure, the divertor will favor counting intervals that take place just before scheduled instrument maintenance. It is assumed that after instrument maintenance the instrument is operating properly with a probability equal to one. The determination of an optimal diversion strategy is complicated by the fact that instrument performance is not stationary but changes with time. Although this does not preclude analysis, it introduces a significant computational burden in requiring additional arcs to represent the various counting intervals. For very low instrument-failure rates, it may be possible to achieve a sufficiently accurate analysis by breaking the total time horizon into only a few relatively long periods. Each time period will include many counting intervals with the assumption that instrument performance is constant within each period.

Instrument alarm thresholds are generally set as low as possible, subject to an acceptable systems false-alarm probability. In practice, it may not be possible to obtain this setting exactly, and thus, calibration will produce an error that is propagated from one measurement to another. Generally, it is assumed that this error, sometimes referred to as systematic error, can be represented by a normal density function with mean zero, and once introduced, it remains fixed until subsequent instrument calibration. Although this error varies randomly from one calibration to another, it produces a bias in all measurements taken between calibrations. Therefore, it cannot simply be treated as a source of measurement variance like that associated with the randomness in the number of counts produced by background radiation.

Calibration error destroys the independence in measurement outcomes between counting periods. With the loss of independence, the detection avoidance function over several time increments is no longer the product of the individual functions because the detection avoidance function for every counting period is conditional on the outcome of the calibration. If the error produced by calibration is small relative to the actual mean and variance of the background radiation, the effect of calibration error may be negligible. Nevertheless, this systematic error is likely to be of major consequence when separate measurements are accumulated to determine whether diversion has taken place. This occurs because, when systematic error is allowed to accumulate, it can eventually dominate all random sources of error. For a penetration-monitoring system, deciding to sound an alarm is based on a single measurement and not on an accumulation of measurement values, and thus, calibration error is less important.

With the solution method described here, it is not possible to include calibration error in determining the optimal diversion strategy. However, for any specific strategy it is possible, though cumbersome, to recalculate the detection avoidance probability so that the influence of calibration error is explicitly considered. The extent to which calibration error creates changes in the optimal diversion strategy was not considered in this study.

In evaluating systems performance for the reference facility, systems sensitivity $P(d,\underset{\sim}{m}^*)$ and the expected false-alarm rate N_f/T were computed and the results are shown in Section V.B. Calibration error was assumed to be negligible and reliability was not considered because no data were available. Sensor performance characteristics used in the evaluation are discussed in the next section.

III. CONTAINMENT/SURVEILLANCE SENSOR PERFORMANCE

The probabilistic characterization of surveillance device performance involves specifying the probability of detecting the movement of, or access to, nuclear material through the instrumented penetration. This probability is expressed, analytically or graphically, as a function of the amount of nuclear material removed. This function is associated with an implicit characteristic time period that may differ from the time interval for which the containment/surveillance system is evaluated. In the following section, probability of detection functions are proposed for each of the surveillance devices that are included in the reference containment/surveillance designs.

The pipe radiation monitors considered for this example are neodymium-glass alpha scintillators, which measure plutonium concentration. Detector response (that is, the number of counts N) is assumed to be characterized by a Poisson density distribution; however, for a sufficiently large mean number of counts, a Poisson distribution may be adequately approximated by a normal distribution with variance equal to the mean. The mean number of counts is given by

$$\bar{N} = \bar{b} + \alpha C \quad ,$$

where b is the mean background, α is a calibration constant, and C is the plutonium concentration. If an alarm level is set to indicate when the number of counts exceeds a particular number, for that particular alarm level with a particular mean background and counting time, a probability of detection vs plutonium concentration may be obtained by integrating the probability density function for various concentrations.

The amount of material removed through the pipe during a counting interval is the product of the flow rate, counting interval, and concentration. Thus, the probability of detecting an amount of material m is taken to be $P_D(C_m)$ where

$$C_m = \frac{m}{\pi r} = \text{minimum concentration associated with the removal of } m \quad .$$

Here π is the counting time (1 min), and r is the maximum credible flow rate (100 mL/min). $P_D(m)$, which is equivalent to $P_D(C_m)$, is therefore dependent both on the characteristics of the surveillance instrument and on characteristics of the penetration. The resulting performance curve is shown in Fig. C-2. This performance function was calculated assuming a mean background of 10 100 counts/min, and an alarm level set at $4.75\sigma_b$ above mean background.

Liquid-in-line sensors have been shown experimentally to trigger with high probability when the liquid volume fraction (V) within the pipe exceeds 0.2 to 0.5 depending on the sensor type. For purposes of this exercise, $P_D(V)$ is assumed to be linear with $P_D(V \geq 0.4)$ equal to unity. The total amount of material removed during the time interval (τ) between interrogation of the sensor (taken to be 1 min) is given by

$$m = V \tau r C'_m \quad ,$$

where r is the maximum credible flow rate and C_m is the maximum credible plutonium concentration. Thus $P_D(m)$ is assumed to be $P_D(V_m)$ where

$$V_m = \frac{m}{\tau r C'_m} \quad .$$

A maximum credible plutonium concentration (C_m) of 250 g/L and a maximum credible flow rate of 100 mL/min were assumed. This function is also shown in Fig. C-3. These devices are assumed to have a false-alarm rate of 1×10^{-8}/min.

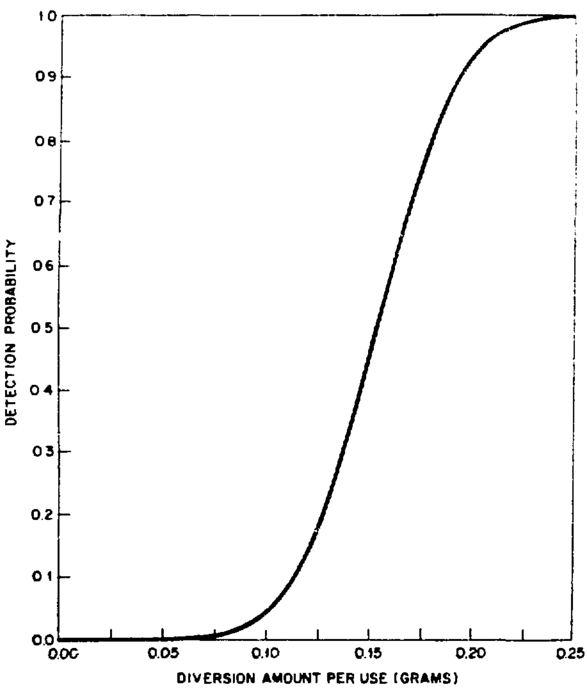

Fig. C-2. Pipe radiation monitor detection function.

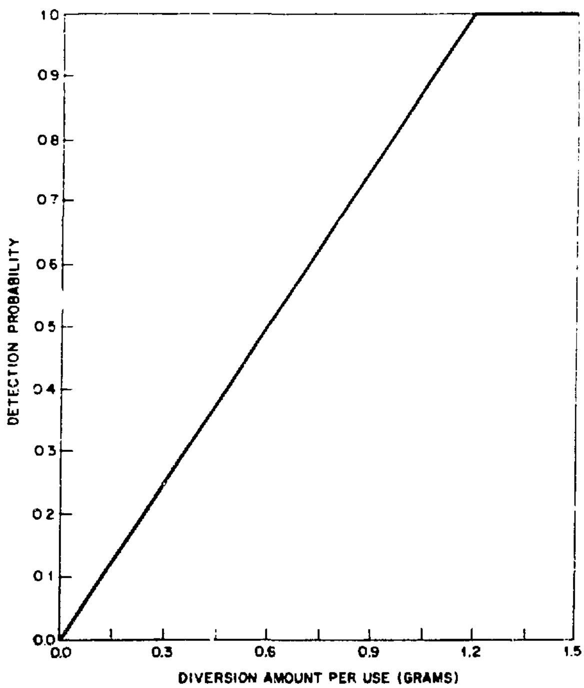

Fig. C-3. Liquid-in-line monitor detection function.

The performance function for personnel portal monitors was presented in Ref. 4 and is shown in Fig. C-4. Detection threshold is assumed to be set at a level corresponding to a false-alarm probability of 3×10^{-4}/use. Instead of a characteristic time, the probability of detection is expressed in terms of a single pass through the detector.

The equipment portal monitor performance is modeled for this exercise by the function given in Fig. C-5. This device is also characterized by a probability of detection per use and a false-alarm probability of 3×10^{-4}/use.

The sample counter that monitors the number of samples removed from the primary containment was modeled as shown in Fig. C-6. No indication is given by this device until the number of samples taken exceeds the maximum number expected. The characteristic time for the device is taken to be one day. The threshold amount of material removed is the product of the number of samples and the maximum plutonium content of a sample (2.5g). A false-alarm rate of 1×10^{-3}/day is assumed.

The probability of detection of a status indicator is expressed on a per use basis but is assumed independent of the amount of material removed because this device detects access to material and not material movement. The performance function for status indicators is shown in Fig. C-7. False-alarm rate is assumed to be 1×10^{-2}/yr.

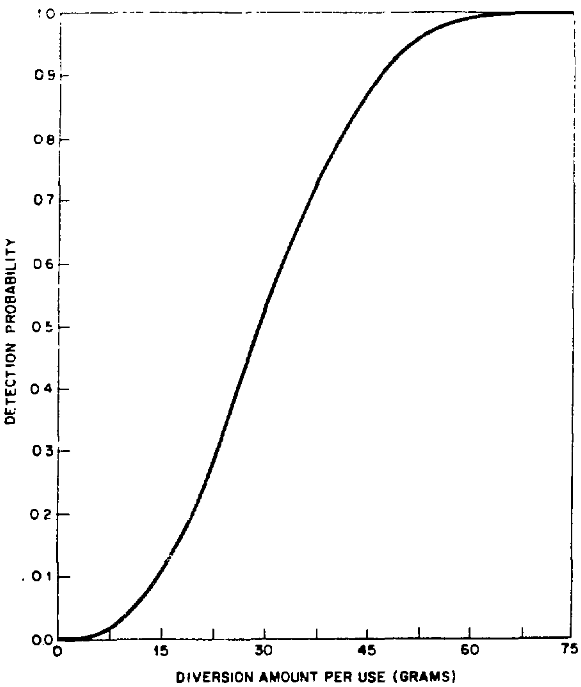

Fig. C-4. Personnel portal detection function.

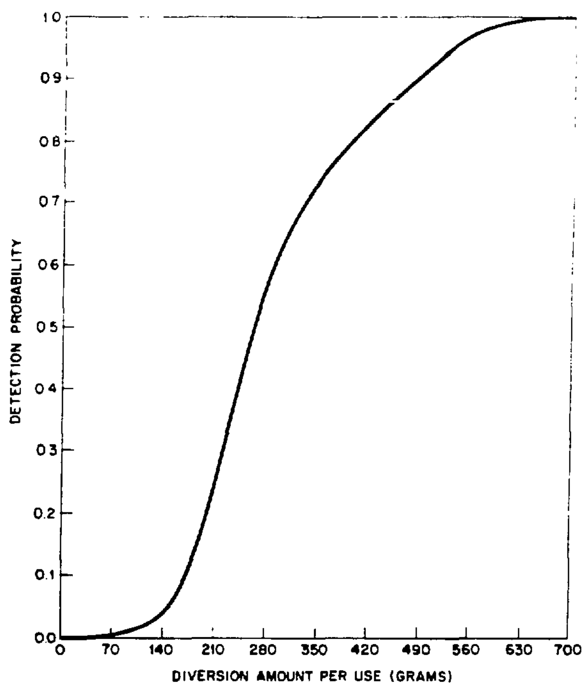

Fig. C-5. Equipment portal detection function.

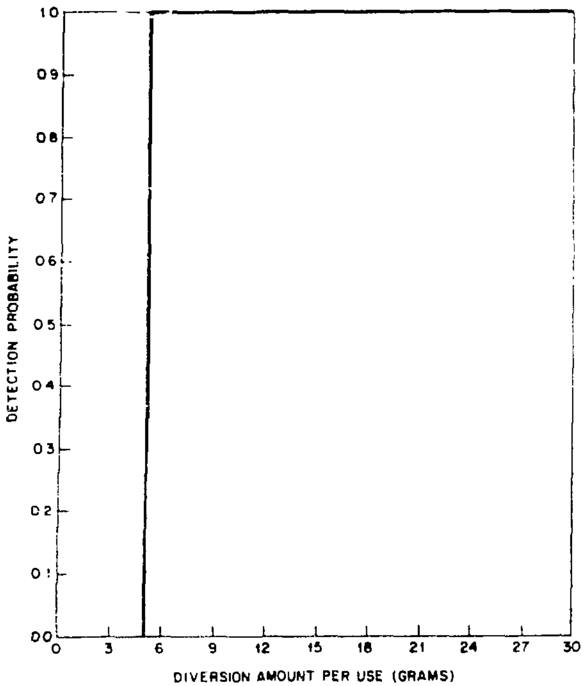

Fig. C-6. Sample counter detection function.

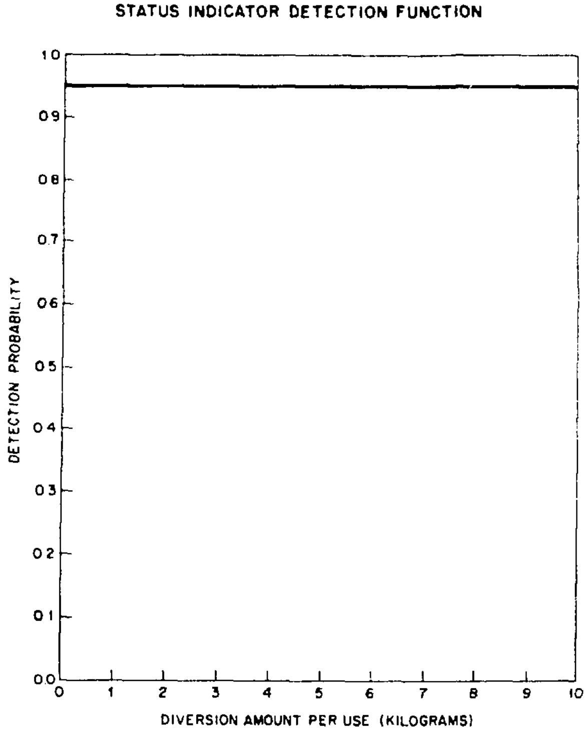

Fig. C-7. Status indicator detection function.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1982-0-576-020/2