DR-52

ALO-0789-T5(Rev.)

# Integrated IAEA Safeguards Concepts for Nuclear Critical Facilities

August 1979

440 copies

Prepared for

U.S. Department of Energy

Assistant Secretary for Defense Programs
Office of Safeguards and Security



Under Contract No. EY-76-C-04-0789

## NOTICE



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Price: Paper Copy $4.00
Microfiche $3.00

Printed in the United States of America
USDOE Technical Information Center, Oak Ridge, Tennessee

ALO-0789-T5(Rev.)
Distribution Category UC-15

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# ACKNOWLEDGEMENT

This document summarizes work performed at Argonne National Laboratory, Los Alamos Scientific Laboratory, and Sandia Laboratories.

# SUMMARY

A study was undertaken to investigate concepts for international safeguards at critical facilities which would minimize impact on normal operations. Only high-inventory critical facilities were considered.

A selection of possible system parameters was incorporated into 28 different international safeguards system concepts, one of which was identified for additional evaluation. If this system were implemented, it would involve methods of monitoring movement of materials and people and would maintain a running inventory that is tested periodically by independent inventory sampling. This monitoring would detect inventory and procedural discrepancies a well as unauthorized removal of nuclear materials. A special inventory may be taken following a monitoring alarm to confirm a suspected diversion. Comparison of various safeguards options led to the selection, for further development, of a system which uses a combination of surveillance and inspection by resident International Atomic Energy Agency (IAEA) personnel, containment/surveillance by unattended equipment, and periodic routine inventory verification.

Evaluation techniques were used to establish that this system is likely to have a high probability of detecting the protracted diversion of a significant quantity of nuclear material. It was also established that practical containment and surveillance measures are necessary but may not be sufficient to achieve timely detection. However, due to current limitations in evaluation methods for assessing containment and surveillance, overall system effectiveness was not quantified.

The safeguards system concepts were developed for a reference critical facility having a split-table horizontal matrix; however, a system designed for an actual facility would necessarily incorporate facility-specific features. Development of special equipment for such systems must include preliminary operational tests and evaluations of these concepts in an operating facility to determine their effectiveness and acceptability.

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# CONTENTS



# FIGURES



# TABLES

# I. INTRODUCTION

## A. Background

The United States, through the Program for Technical Assistance to the IAEA and the Department of Energy's Office of Safeguards and Security, is sponsoring the development of advanced concepts for providing international safeguards at fast critical facilities. These facilities are located in non-weapons as well as weapons states. Several of these facilities will be coming under IAEA safeguards. They present a unique safeguards problem because each facility uses fuel plates, pins, or arrays containing multiple significant quantities of fissile material in relatively pure form.

References 1 and 2 are studies undertaken to investigate techniques for containment and surveillance and to investigate companion techniques for rapid materials measurement and timely verification of the facility inventory. Analysis of the integrated safeguards system that results from combining these techniques has indicated that there is a high level of protection against the threat that some portion of the fissile inventory might be diverted, without detection, to the production of nuclear weapons.

Prompt detection of a significant diversion must rely on stringent, tamper-indicating containment and surveillance measures such as placing unattended containment/surveillance instrumentation at portals and frequently inspecting safeguarded areas to verify containment integrity. Inventory verification procedures must be provided to assure that the containment and surveillance measures have not been subverted or bypassed; (for example, by multiple removals of amounts of fissile material too small to be reliably detected by containment and surveillance). In addition, techniques and procedures must be available for a special verification of the inventory in case a diversion is suspected and the IAEA concludes that a special inventory verification is necessary.

This document summarizes international safeguards system concepts, including inventory techniques, inspections procedures, and containment and surveillance methods. These concepts are the basis for a research and development program which will determine technical feasibility and operational acceptability.

## B. Assumptions and Criteria

International safeguards are measures taken to deter, through timely detection, national diversion of nuclear material to non-peaceful uses or to purposes unknown. Materials accounting is a safeguards measure of fundamental importance, and containment and surveillance are important complementary measures. The importance of materials accounting stems from the necessity of maintaining continuity of knowledge, both in time and in location, about the state of nuclear material within the nuclear fuel cycle. Containment and surveillance techniques complement the materials accounting functions and can be used to promptly detect illicit activities involving nuclear materials.

Fuel elements used in fast critical facilities are considered "direct use" material in that they may contain plutonium, uranium-233, or uranium enriched to ≥20 percent in uranium-235. An international safeguards system should have a high probability of timely detection of the amount of these materials which could be directly used to produce nuclear explosives (threshold amount). The detection goal (significant quantity) may be different from the threshold amount under some circumstances, but for high-inventory fast critical facilities, they are considered to be the same. The significant quantities for the types of materials found at critical facilities are assumed to be 8 kg plutonium, total element (Pu-238 ≤ 80 percent); 8 kg uranium-233, total isotope; and 25 kg uranium-235, total isotope.

Ideally, the time between the diversion of a significant quantity and the detection of the diversion should be no greater than the time necessary to convert (coversion time) the various nuclear materials into forms usable for nuclear explosives. Unirradiated "direct use" materials have relatively short conversion times, since they do not require chemical separation of fission products nor do they require isotopic enrichment. Estimates of these conversion times range from days to weeks. Therefore, a desirable goal for detection time for "direct use" materials found at fast critical facilities is detection within 1 week of the completion of the removal of a significant quantity from the facility.

Frequent on-site inspection activities are essential for effective international safeguards at large critical facilities. Frequent inspections are permitted by specific bilateral and non-proliferation treaty (NPT) provisions. They follow from the need for independent routine inventory verification and other activities which must be performed by inspectors. These activities include equipment maintenance and calibration, verification of tamper-safing features, observation of routine and non-routine operations such as removal of large equipment from material access areas, and surveillance for unauthorized activities such as facility modifications.

An international authority must require confirmation of a suspected diversion—possibly by means of a special physical inventory—since an accusation that a state has diverted material is reported to all member nations. Hence it is assumed that the required high assurance would be achieved by physical inventory verification.

An international safeguards system for fast critical facilities should have the demonstrable capability of meeting a number of basic requirements and conditions, including the following:

1. High probability of detecting diversion,
2. Timely detection of diversion,
3. Acceptably low probability of false alarm,
4. Acceptably low level of interference with facility operations,
5. Acceptable cost,
6. High reliability, and
7. Low maintenance.

Both prolonged diversion of small quantities of material in multiple attempts, with the intent of avoiding detection, and abrupt diversion of major amounts of material between periodic application of safeguards must be considered.

Because several of the basic requirements, conditions, and safeguards goals tend to be mutually exclusive, some compromises must be made. However, the resulting system must be capable of demonstrating a credible detection capability within a facility operational environment.

# II. INTERNATIONAL SAFEGUARDS APPROACH

International safeguards conducted by the IAEA rely on routine reporting and periodic inspection by IAEA personnel. To meet timeliness criteria, periodic inspections by themselves are not adequate.

Figure 1 outlines the international safeguards system approach that was used as a basis for the concepts. Continuous monitoring bridges the time between the periodic safeguards decision points associated with the international safeguards. This monitoring may be accomplished by inspector surveillance, by unattended instrumentation, by routine sampling of the inventory, or by a combination of these methods. Unauthorized actions that could indicate a diversion are sensed by the

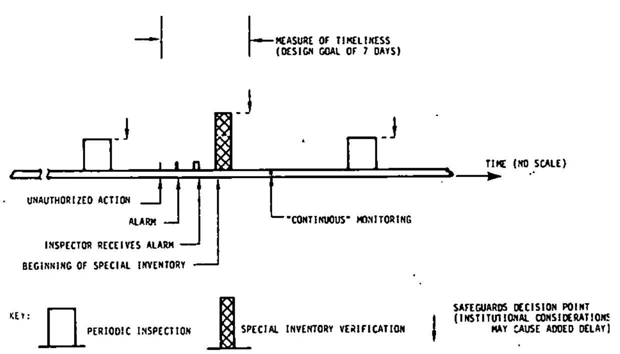


**Figure 1.** International Safeguards

monitoring system and cause an alarm to be generated. The alarm in turn is received by the international authority. Response to an alarm is first an assessment and may be followed by a special inventory verification if necessary. This sequence provides the necessary information to reach a safeguards decision. The measure of timeliness in this approach is the interval from the unauthorized action (completion of a diversion of at least a significant quantity) to the safeguards decision point at the end of the special inventory verification. The times between unauthorized action, alarm, receipt of alarm, the beginning of the special inventory, and the safeguards decision are system variables that depend upon inspection procedures, communication, and safeguards equipment.

This system approach, because it incorporates special physical inventory verification procedures that can be disruptive to normal facility operations, must have an acceptably low likelihood of false alarms. Cooperation by the facility operator in minimizing false alarms can and should be encouraged by the safeguards authority through agreed-upon administrative procedures monitored by the safeguards system. Any violation of these procedures would result in an alarm that may require a special inventory verification. The degree of this inventory effort will depend upon the nature of the alarm and the suspected strategy of diversion. It is important to recognize that for a given inspection procedure there is a continuum of statements that can be made concerning the probability of detection and the amount of material diverted. For example, in a given inventory verification, the probability of detecting a diversion will be low for a small amount of material and, simultaneously, high for a large amount of material. Seen from a different perspective, a system that is adequate to detect the abrupt removal of large amounts of material may have a limited capability of detecting the prolonged diversion of small quantities of special nuclear materials (SNM).

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# III. SAFEGUARDS SYSTEM CONCEPTS

The approach to international safeguards described in Section II provides a basis for developing integrated safeguards system concepts that combine inspection, materials accountability, and containment/surveillance measures. The concepts, described in the following pages, were developed for a model critical facility. This reference facility is descriptive of a large critical facility having a split-table assembly. The model incorporates realistic features of an operating facility in sufficient detail so that specific concepts could be considered. The actual safeguards system for any real facility must be developed with regard to facility-specific design and operating features. For example, vertical integral critical assemblies have massive fuel assemblies rather than readily accessible open drawers and may require safeguards procedures that differ significantly from those for split-table assemblies.

To develop a system directed toward meeting international safeguards goals, a number of safeguards options, strategies, and procedures were considered for the model facility. Materials accountability techniques such as sampling, item identification, and materials measurement provide safeguards measures that can be quantified as to detection thresholds and probabilities. However, because of the large number of fuel pieces in a large critical facility, the use of materials accountability to detect the abrupt diversion of a significant quantity of material within approximately 1 week of the completion of the diversion is probably not feasible. On the other hand, materials accountability can provide a high level of detection probability (~0.95) for detecting the protracted diversion of small quantities of material over an extended period of time. The timeliness goal may not be met by materials accountability, but detection will be achieved.

In contrast, containment and surveillance techniques provide detection capabilities that are generally difficult to quantify in the absolute sense because of the need for quantifying human action. However, containment/surveillance measures can provide timely detection, particularly for abrupt diversion of a significant quantity. Some containment and surveillance devices, such as portal monitors and optical surveillance equipment, have detection thresholds that can detect the removal of small quantities (on the order of grams per try) of nuclear material. A properly designed safeguards system must include materials accountability to verify that containment/surveillance measures have not been bypassed (for example, by multiple removals of fissile material in amounts smaller than the detection capability of a portal monitor).

The key elements of the safeguards system selected as a result of this study are listed and then several are described in detail. They are

1. Routine inventory verification on a periodic basis,
2. Containment of nuclear material by the structural features of the facility and by unattended SNM portal monitors at the perimeter of the material access area,
3. Inspector presence during movement of any material that cannot pass through portal monitors,
4. Frequent visual inspection of the facility to detect unusual activity or structural alterations,
5. Use of seals on containers of stored SNM to reduce inventory verification requirements, and
6. Special assessment and verification procedures when unauthorized actions or indications of diversion occur.

**Inventory Verification**—Inventory verification procedures for this systems concept have two essential functions: (1) routine inventory verification and (2) special assessment and verification if the inspectorate suspects that diversion has occurred. When fuels are not in use in a critical facility reactor, they are placed in containers and stored in a vault. Seals should be used on the vault storage containers and the contents of each storage container verified by non-destructive assay (NDA) measurement. The use of seals and NDA measurements can substantially reduce the effort required for routine or special inventory verification. With this strategy, seals and verification measurements are applied routinely to the static portion of the vault inventory. Maintaining the entire vault inventory under continuous seal is not required. Because the vault is accessible during reactor operation, the application of seals to and the taking of verification measurements from storage containers during normal working hours need not interrupt the experimental program. The required inventory effort can be reduced further by sealing that portion of the vault inventory not scheduled for near-term use in reactor experiments.

Because the many fuel pieces in the inventory are in reactor fuel drawers and vault storage containers, an inventory verification based on measuring individual fuel pieces is time consuming and adversely affects the productivity of the experimental program. It is desirable, therefore, to inventory the fuel "collectively", in relatively large units, and to integrate these collective verification measures as much as possible into the normal facility operation without requiring extended shutdown periods. Collective-measurement techniques for verification of critical-facility fuels include gamma-ray and neutron NDA, autoradiographic NDA, and integral reactivity and related reactor-parameter measurements. Table I is a summary of possible measurement techniques, including the capabilities and possible limitations of each. The measurements are sensitive to different properties and characteristics of the SNM fuels. Although it may be possible to subvert any one measurement technique, a combination of these techniques provides increased assurance and reduced vulnerability.

**TABLE I**

Materials Measurement Techniques

| Measurement Type | Capabilities | Limitations |
|---|---|---|
| Gamma spectroscopy | Isotopic ratios; fissile Pu content | Significant self-attenuation; affected by background; marginal for Highly Enriched Uranium (HEU) fuels; fuel handling required |
| Passive neutron<br>Total counts | Content of even Pu isotopes; relatively simple instrumentation | Fissile Pu isotopes not measured directly; affected by ($\alpha$, n) reactions; affected by neutron background; fuel handling required; no HEU fuels |
| Passive neutron<br>Total and co-incidence counts | Content of even Pu isotopes; sensitive to changes in geometry; corrections for background and ($\alpha$, n) reactions | Fissile Pu isotopes not measured directly; fuel handling required; no HEU fuels |
| Active neutron | U-235 content of HEU fuels; total fissile content of mixed (U, Pu) fuels; can be operated in passive mode for Pu | External radiation source required; relatively bulky and complex instrumentation; fuel handling required |
| Autoradiography | Image of edge area of each Pu fuel piece; very fast; minimum fuel handling; relatively simple and inexpensive. | Surface effect; may not be SNM specific; film processing and reading required |
| Reactivity | Total in-reactor inventory; very sensitive | Relatively easy for operator to subvert by itself; supplementary measurements required; some fuel handling required |
| Material worth | Reactivity-compensating changes in fuel density neutron spectrum, and power profile | Supplementary to reactivity measurement |
| Foil activation | Reacticity-compensating changes in fuel density neutron spectrum, and power profile | Supplementary to reactivity measurements |

Reactor inventory verification is an especially difficult problem in safeguarding fast-critical facilities. Options for reactor inventory verification generally fall into two categories: (1) those requiring "in-line" verification during normal fuel handling and (2) those requiring periodic verification of the reactor inventory. The selection of the best combination of inventory verification options depends on specific design and operating features of the fast critical facility.

Category 1 options have several safeguards advantages because of the possibility of measuring all fuel entering and leaving the reactor by NDA techniques. For example, a unique measurement signature could be determined for each fuel assembly (drawer) when it is loaded initially. Later, when the fuel element is unloaded from the reactor, it is remeasured and its contents are verified by a simple yet very sensitive comparison of measurement signatures. The reactor cell would have to be sealed or maintained under continuous surveillance between loading changes. During operations, at least one inspector would have to be present in the facility. Category 1 procedures may be suitable for facilities having vertical assemblies. Fuel elements in the model facility (split-table assembly) are open metal drawers, and the use of Category 1 procedures would impose a potentially unacceptable burden on both the inspector and operator. Since an average of more than 200 fuel drawers are transferred to or from the model facility reactor each week, sealing or effective surveillance would be difficult.

Category 2 options include all procedures for periodic verification of the reactor inventory. These options can provide adequate verification of reactor inventory without frequently unloading the reactor or obstructing normal material flow paths. The following paragraphs describe a conceptual approach to reactor inventory verification for a split-table fast critical facility. Specific elements of this approach depend on assumed design and operating features of the model facility, such as automated fuel-handling capability and accessibility of reactor drawers for NDA measurement. This verification strategy is illustrative only. The strategy developed for any real facility may differ.

Inventory in the reactor is verified at 1- to 3-month intervals by randomly selecting a combination of sampling and reactivity verifications. Two or three inspectors are present during a routine verification. Reactor downtime during each routine verification is limited to two 8-hour shifts (maximum of 20 shifts annually) that can be scheduled during non-operating hours. Automated fuel handling is used to minimize radiation exposure to personnel. If sampling is used for verification, approximately 10 percent of the reactor inventory using a combination of NDA techniques to measure fuel in reactor drawers. If a reactivity verification is used, the reactor is loaded in a reference configuration. The gross reactivity and other parameters of the reference that are sensitive to possible reactivity-compensating changes are checked.

When an abnormal safeguards condition occurs, the inspector investigates the cause. If the Agency is convinced from its investigations that there could have been a diversion from the facility, it may require a special inspection to confirm the diversion and identify the form and quantity of missing material. A special inspection includes auditing the facility records, checking the integrity of sealed inventory, and verifying the unsealed inventory. The inspectorate should develop a special inspection plan based on the evidence concerning the inspected diversion strategy. For example, this plan could include a sampling verification of 50 percent of the reactor inventory, which would provide >95 percent probability of detecting a missing significant quantity. It is estimated that a team of about six inspectors could complete a special inspection of the model facility in 1 to 2 weeks.

**Containment/Surveillance Measures**—The reactor building structure provides a natural safeguards perimeter where containment/surveillance measures can be applied. In the model facility there are three exits through which nuclear material might be diverted. Containment/surveillance methods for safeguarding these exits and for verifying the integrity of the reactor containment are described below.

All personnel and material moving out of the material access area are monitored for nuclear material. Items that are too large for the detection equipment require the presence of an IAEA inspector to monitor the flow of material. Routine inspections of the facility structure for evidence of diversion through abnormal paths are required. A diagram of the containment/surveillance conceptual design as applied to the reference facility is shown in Figure 2. These containment/surveillance techniques complement the material accountancy measures, and failure of containment/surveillance, though degrading to the effectiveness of the safeguards system, does not result in inability to detect diversion; it does, though, result in loss of timeliness.

Detection of diversion at the corridor to the control room is accomplished by a personnel portal monitor, which contains a passive nuclear material detection system and an active system for metal detection; and by a material passthrough portal which utilizes a neutron-activation detection

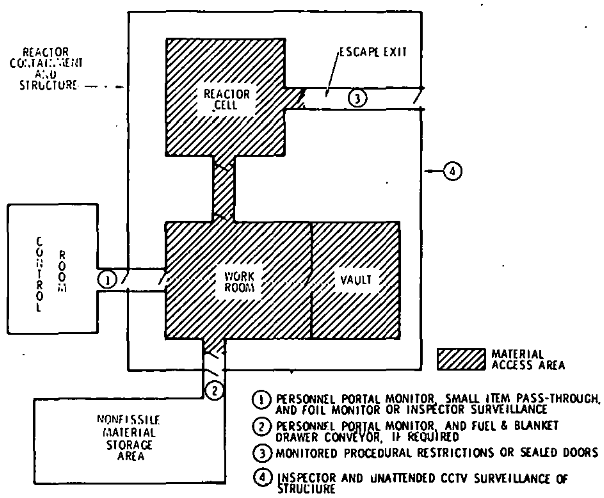


**Figure 2.** Conceptual Design of Model Reference Containment/Surveillance System

scheme. The movement in and out of the material access area of small quantities of diagnostic uranium and plutonium foils (which is not a daily operation) requires the presence of an IAEA inspector. Both the personnel portal and the material passthrough have two doors interconnected to provide an alarm if both doors are open at the same time. This prevents material from being thrown through the portal. To assure an acceptably low false alarm rate, all personnel and material passing through the portals will be automatically interrogated several times. An alarm will occur only if there is detection on all interrogations followed by an exit from the portal. The IAEA instrumentation must be tamper-safe to protect both equipment and information from unauthorized access.

Nuclear material detection at the corridor to the material storage area is accomplished by two portal monitors: a personnel walkthrough and a material passthrough allowing passage of drawers containing nonfissile material. When other items too large to pass through the material passthrough are removed from the facility through doors which bypass the monitors, the presence of an inspector is required. When not in use, the doors are secured with IAEA-approved seals. The personnel portal has the same features as the portal in the corridor to the control room. The drawer passthrough portal consists of a neutron-activation detector and a conveyor for transporting the drawers between the material access area and the storage area. Both portals require tamper-safing features. An alternative to the drawer passthrough exists at the reference facility. A location could be included inside the material access area to store the nonfissile reactor material. The final selection would depend upon cost, operational impact, safeguards effectiveness, and physical layout of an actual facility.

The preferred method of safeguarding the escape exit is to apply a seal to one or more of the doors and to verify seal integrity on a routine basis. When inspection or maintenance of the exit is necessary, the inspector would have to be present to monitor these activities. An alternative method for safeguarding this exit which could reduce inspector participation is monitoring the direction of traffic. Routine exit from the facility is not allowed. Limited movement is permitted from outside to inside for inspection and maintenance of the emergency doors. A violation of either of these procedures would be detected by the monitors, and a special inventory could be required.

**Inspection Procedures**—The conceptual strategy for safeguard inspections at fast critical facilities includes the following:

1. Frequent visits are made by one inspector to perform routine safeguards procedures that include (a) checking the containment and surveillance systems, (b) verification of the integrity of the reactor containment structure, (c) calibrating safeguards instrumentation, and (d) sealing the material in vault storage that is not part of the current dynamic inventory. The inspector is on call for special or abnormal operational situations.
2. Perform routine verification of the reactor inventory periodically using a sampling plan and/or integral reactivity measurements.
3. If diversion is indicated and a special inventory is necessary to determine the amount of missing material, a team of six or more inspectors should be available to complete the special inventory within 1 week. The inventory team would check the sealed portion of the vault inventory and would seal and verify the unsealed portion. Sampling and measurement of $\sim$50 percent of the reactor inventory would determine with a high level of assurance whether a significant quantity of material is missing.

# IV. SYSTEM ASSESSMENT

## A. Operational Impact

Personnel knowledgeable in the operation of fast critical facilities have made estimates of the operational impact that the conceptual safeguards system could cause to the reference facility. These estimates are preliminary in that the concepts and equipment have not been field-tested and/or thoroughly evaluated. Details of applying some of the safeguards concepts will probably change as development, test, and evaluation programs proceed. Means of reducing operational impact will evolve as the problems are more thoroughly understood and as estimates yield to actual data.

The safeguards impact analysis for the containment and surveillance aspects of the safeguards system was based upon the concepts described in Section III and upon the following assumptions:

- A resident inspector is present at the reference facility.
- Inspection causes 5-minute delays for all items entering or leaving through the large material hold.
- No significant storage of fuel drawers is allowed in the workroom because of space limitations.
- The two-man system is used so that when a delay is incurred at the portal monitors, this delay affects two people.
- A drawer monitor is used to scan reactor drawers containing nonfissile material when they are removed from the material access area.
- When an employee is delayed, the facility operation is delayed only according to the fractional loss of manpower. However, when materials are delayed, both the facility operations and personnel are delayed.
- When operations are delayed, the whole staff is delayed; however, the delay affects only those involved in the particular operation and/or loading change.
- A 6.5-hour day was used in arriving at lost-man-days and facility-days.

A tabulation of activities which would be expected at the model reference facility and estimates of man-days and facility-days lost per year were made. Included were such activities as core loading and unloading, personnel movement into and out of the material access area, movement of large items, and time required to use the drawer monitor. Based on the above, the following estimates were made:

- The total lost facility time due to physical safeguards may be as much as 55 days per year, or 23 percent of present facility operating time. (Includes access control for the state system.)
- The use of the drawer conveyor monitor causes almost one-half of this lost facility time.
- The total lost effort is approximately 546 man-days, or 2.3 man-years.
- The use of the drawer conveyor monitor causes approximately two-thirds of the lost effort; if provisions were made to store the non-fuel material within the material access area, the facility lost time would be reduced to 13 percent and lost manpower to approximately 1 man-year per year.

Initial evaluation of the operational and manpower impact of the material accountability concepts for the model facility were also undertaken and were based both upon the previously stated assumptions for estimating containment and surveillance impact and upon the additional assumptions which follow:

- The period between routine verification is no less than 1 nor more than 3 months with a total of 6 to 10 verifications per year.
- The routine verifications are at the 10-percent sampling level.
- Routine inventories would be conducted on an overtime basis to reduce facility downtime.
- Whenever possible, remote core loading and unloading would be used to minimize personnel radiation exposure.
- Special inventories are at the 50-percent sampling level.

The procedure for estimating these impacts involved (1) identifying the operations involved, (2) estimating the manpower and time required to remove, handle, and replace items to be inventoried, and (3) determining the schedules and procedures that would tend to minimize facility downtime. Using this procedure with the best estimates available and without benefit of actual operational tests, the following estimates were made:

- Aspects of routine inventory verification that would shut down the facility could probably be accomplished outside of normal working hours.
- If routine inventory were accomplished during day shifts, approximately 8 percent of the facility output would be lost.
- At least 1 man-year of facility effort would be required each year to support routine verification.
- Special inventories, using remote fuel handling at the critical assembly, should require ten 8-hour shifts for a 50-percent sampling verification.

Manual handling of fuel for a special inventory would be much faster, but could result in excessive radiation exposure to personnel.

## B. System Effectiveness

The complimentary detection capabilities of the components and the proposed safeguards system are reviewed in Figure 3, which is a flowchart showing the generic sequence of actions required for successful diversion. Routine inventory provides the primary means for detecting inventory discrepancies both within the material access area and during shipping and receiving operations. A backup capability is provided by inspector surveillance. Diversion involving strategies of material substitution and/or record falsification are detected by routine inventory verification and inspection. Detection by routine inventory may not always be timely, but it does provide high confidence in assuring that protracted diversion has not ocurred.

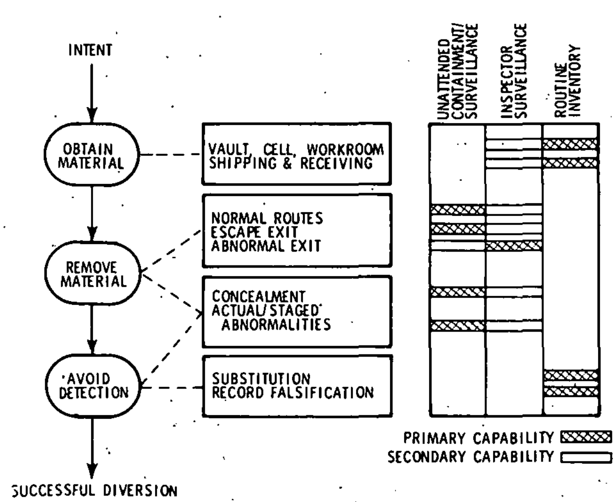


**Figure 3.** Detection Capability

Inspector surveillance provides the principal capability to detect unauthorized structural changes that could facilitate removal along abnormal exits such as holes in the reactor containment or modifications of the ventilation system. Inspector surveillance also provides a valuable secondary capability for detecting abnormal activities that might occur during allegedly normal operations.

Unattended containment/surveillance is the primary means for detecting removal of material through facility exits, either by concealment or during actual or staged emergencies. This capability effectively extends the coverage of the inspector by providing unattended monitoring of these exits when the inspector is engaged in other activities.

Combined effectiveness of the proposed international safeguards system is based on the effectiveness of the respective roles of these basic safeguards measures. Materials accountability, though it may not meet the timeliness goals, can provide quantitative assurance. Containment/surveillance measures, though generally not quantitative, can provide a prompt alarm, particularly for the strategy of abrupt diversion.

**Inventory Verification (Reactivity Method)** — The effectiveness of reactivity verification of the model facility's reactor inventory was estimated using modeling and simulation techniques based upon data from an operating critical facility and upon the assumption that fuel was removed from minimum-worth regions of the core. Additional analysis is necessary to determine if other methods such as control rod positioning, which might be used to mask fuel removal, are possible.

Measurements of integral reactivity made on a well-characterized reference configuration are very sensitive to small shifts in the reactor inventory. Supplementary measurements are required to verify that reactivity-compensating changes have not been made in the reference configuration. Table II gives calculated detection limits corres-

**TABLE II**

Detection Limits* For Integral Reactivity Checks (Eight Reference Configurations)

| Configuration Number | Detection Limit for 1-Inch Removals (kg Pu) | Detection Limit for 4-Inch Removals (kg Pu) |
|---|---|---|
| 1 | 0.37 | 0.31 |
| 2 | 0.37 | 0.31 |
| 3 | 0.35 | 0.29 |
| 4 | 0.53 | 0.42 |
| 5 | 0.46 | 0.38 |
| 6 | 0.34 | 0.27 |
| 7 | 0.28 | 0.23 |
| 8 | 0.44 | 0.35 |

*Corresponding to a 3-Ih change in reactivity produced by removing fuel from regions of minimum worth.

ponding to a 3-Ih (In-hour) reactivity change that would have been produced in various reference configurations, by removing fuel from regions of minimum worth; that is, from the core region that is least sensitive to fuel-loading changes. In all cases, a shift of considerably <1 kg of plutonium is detected out of a reactor inventory of more than 1,000 kg.

**Inventory Verification (Material Sampling)**— Table III gives the probability of detecting 8 kg of plutonium from the reactor in whole-drawer amounts with bimonthly 10-percent samples. The detection probability is near 95 percent after 6 months; that is, after 30 percent of the reactor inventory has been sampled. Each 10-percent sample also provides a 95-percent probability of detecting ~30 kg missing from the reactor inventory.

**TABLE III**

Probability of Detecting 8 kg of Missing Plutonium
(Whole-Drawer Diversions)

| Detection Time (months) | Cumulative Fraction Sampled (percent) | Detection Probability (percent) |
|---|---|---|
| 2 | 10 | 61 |
| 4 | 20 | 82 |
| 6 | 30 | 93 |
| 8 | 40 | 97 |
| 10 | 50 | 99 |
| 12 | 60 | 99 |

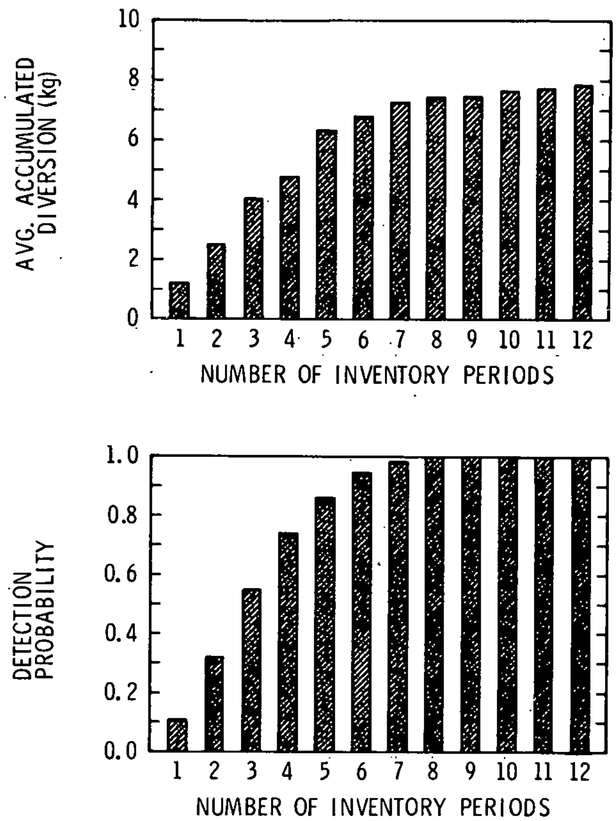


**Figure 4.** Protracted Diversion

Figure 4 shows the probability of detecting the protracted diversion of 8 kg of plutonium with monthly 10-percent sampling. The diversion strategy consists of randomly removing 4 kg in whole-drawer amounts and 4 kg in 2.54-cm plate amounts during 6 months of operation. This strategy is almost optimal for the divertor against the combined attributes-variables sampling plan. The detection probability is 95 percent after 6 months, that is, after an average of ~ 7 kg have been diverted. By comparison, bimonthly 10-percent samples provide a 95-percent probability of detecting the protracted diversion of 8 kg during 1 year.

The results of many simulations indicate that the detection probability provided by statistical sampling depends primarily on the cumulative fraction sampled; for example, bimonthly 10-percent samples or semi-annual 30-percent samples provide essentially the same detection capability. This is true for most diversion strategies of interest despite frequent and sometimes rather large changes in the reactor loading during normal operation. There is a continuum of sample sizes and inventory frequencies that can satisfy any given detection goal. The required sample size can be determined, at least as a first approximation, using the elementary binomial sampling formula.

**Containment/Surveillance Measures**—Rating the effectiveness of individual containment/surveillance devices is a new, undeveloped aspect of safeguards systems. It is particularly difficult to evaluate some devices not only because of the many strategies available to the potential divertor, but also because of the necessity to characterize human ingenuity. The potential adversary nature of safeguards adds to the difficulty of assessment. For example, the divertor may have the opportunity to experiment to determine detection thresholds and detection criteria. The role of the system designers is to attempt to minimize the advantage that the adversary might gain from this activity.

Not only must the capability to detect unauthorized nuclear material activities be evaluated, but equipment's level of resistance to the defeat or bypassing of tamper-safing features must be quantified also. In all of these activities and in the final analysis, the judgement of the inspector is involved in detecting unauthorized activities by containment/surveillance measures. Some of these factors are shown in Table IV.

**TABLE IV**

Typical Effectiveness Factors

| Measures | Effectiveness Factors |
| --- | --- |
| Seals and Tamper Indicators | – Resources Required To Bypass<br>– Time To Bypass<br>– Inspection Frequency |
| Optical Surveillance | – Resolution<br>– Time To Image Substitute<br>– Time To Divert<br>– Frequency of Surveillance<br>– Field of View |
| Passive Radiation Detection | – Source Strength<br>– Proximity<br>– Exposure Time<br>– Sensitivity |
| Portal and Package Monitors | – Source Strength<br>– Proximity<br>– Exposure Time<br>– Sensitivity<br>– Frequency of Use |
| Inspection | – Frequency<br>– Intensity<br>– Training |

**TABLE V**

Estimates of Personnel Portal Detection of Unshielded Metallic Nuclear Material*

| Material | Detection Level | | |
| --- | --- | --- | --- |
| | Neutron Detection (grams) | Gamma Detection (grams) | Metal Detection (grams) |
| Plutonium (95 percent 239, 5 percent 240) | 0.6 | 0.3 | 100 |
| Plutonium (88 percent 239, 12 percent 240) | 0.25 | 0.35 | 100 |
| Plutonium (74 percent 239, 26 percent 240) | 0.1 | 0.4 | 100 |
| Uranium (93 percent 235, 7 percent 240) | 43k | 4 | 100 |

*These estimates do not include any neutrons produced by ($\alpha$, n) reactions but only the detection of spontaneous fission neutrons. No mixed plutonium and uranium materials are considered.

By neglecting the behavioral aspects of the quantification problem, it has been possible to estimate the nuclear material detection capability of portals which are under development. Table V summarizes the expected detection capabilities for unshielded metallic nuclear material in a personnel portal which uses neutron detectors (helium-filled proportional counters), gamma detectors (plastic scintillators), and a specially designed volume metal detector.[3]

If the plutonium is in oxide form, there is an attendant increase in the neutron-related detection capability due to the ($\alpha$, n) reactions, and the detectable quantity is smaller by an approximate factor of two. Due to the various combinations of material that can be used to shield the radioactivity associated with the SNM, it is difficult to define detectable quantities of shielded SNM. It is estimated that practical shielding of the neutrons will only reduce the detectable neutrons by an approximate factor of 100. Gammas can be shielded by a factor of 1,000; however, the presence of a metal detector makes undetected gamma shielding of nuclear material difficult.

In the material passthrough portal, nuclear material will be detected by actively inducing fission in the material. It is estimated that less than 25 grams of unshielded uranium or plutonium will be detectable. This estimate is based on theoretical and experimental modeling of the passthrough. Quantities smaller than 25 grams were not considered in the modeling. Determining the detectable quantities of shielded SNM will be accomplished as the development program proceeds. In principle, both the shielded nuclear material and the shielding material will be sensed, but sufficient information is lacking to make meaningful estimates. These estimated detection capabilities suggest that it will be possible to detect the smallest plutonium fuel pieces that were assumed to be in the reference facility fuel inventory (30 grams plutonium). Detection of metallic high fissile content uranium, although not of principal concern for the analysis of the model fast critical facility, is expected to be in the 4- to 100-gram range. Uranium in the oxide form is expected to be more difficult to detect, particularly when shielded with non-metallic material.

# V. CONCLUSIONS

On the basis of this study of component and systems concepts, it is concluded that it is possible to provide international safeguards at fast critical facilities by a complementary combination of resident inspection, materials accountability, and containment/surveillance measures. Equipment and procedures require development before feasibility, operational acceptability, and system effectiveness can be more completely assessed. Materials accountability techniques that need to be evaluated at a fast critical facility include integral reactivity measurement in reference core configurations, autoradiographic item identification, and rapid NDA methods for various fast critical reactor fuels. Containment/surveillance measures that need to be developed, operationally tested, and evaluated at a facility include unattended, tamper-safed personnel portals; instrument/material passthrough portals; television surveillance systems; and sealing techniques to simplify inventory verification. Additional effort must be directed at minimizing operational impact by carefully optimizing inspection and inventory verification procedures.

## References

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