Chapter 7

Nuclear Material Accounting and Control

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CHAPTER OUTLINE

INTRODUCTION

With the advent of the nuclear age, there was concern by states over how to manage nuclear material inventories due to their strategic and financial value and safety risks to both workers and the public, and to deter and detect any unauthorized activities. The need for a systematic approach to account for and control access to nuclear materials drove states to form the foundations of a nuclear material accounting[1] and control[2] (NMAC[3]) system. Not unlike

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[1] Material accounting is defined as the use of statistical and accounting measures to maintain knowledge of the quantities of SNM present in each area of a facility. It includes the use of physical inventories and material balances to verify the presence of material or to detect the loss of material after it occurs, in particular, through theft by one or more insiders. http://www.nrc.gov/security/domestic/mca.html.
[2] Material control means the use of control and monitoring measures to prevent or detect loss when it occurs or soon afterward. http://www.nrc.gov/security/domestic/mca.html.
[3] An equivalent term used is MC&A: Material Control and Accounting.

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systems in use for banking and industry, basic elements began to evolve for accountancy and control using ledgers to record, assay systems to determine isotopic composition and weight, labels to identify contents, and secure locations to store and process these materials. The best parallel would be the precious metals industry where systems were put in place to not only account for and control the inventory but also to support deterrence and detection of both insiders and outsiders who intended to steal these materials.

This became even more acute with the advent of the nuclear fuel cycle (NFC) for the production of energy that would bring nuclear material out of the control of states and into the hands of industry. Nuclear energy was looked to as the future of efficient electrical energy production, and therefore, it was assumed that the use of nuclear energy would rapidly expand to countries around the world. This, in turn, prompted states to set up a regulatory system by establishing a state regulatory authority (SRA) with the legal basis to set forth regulatory requirements for the design and performance of NMAC systems at the nuclear facility level. This system is known as the state system of accounting and control (SSAC).[4] While the SSAC was established as a domestic safeguards system using NMAC, it nevertheless also can meet the requirements for Nuclear Non-Proliferation Treaty signatory states who have safeguards agreements with the International Atomic Energy Agency (IAEA).

BASICS

Although NMAC is applied at the facility level, it remains intimately connected to the SSAC and SRA through regulations, reporting requirements, audits, and, if necessary, corrective actions and strengthening measures. As in any system that is formed with specific goals in mind and where failure can result in severe negative consequences, extensive efforts are made to evaluate the system and address potential weakness so no single point of failure can result in a severe event. Within the nuclear community, this is referred to as defense in depth.[5] While defense in depth is applied to many

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[4] State system of accounting for and control of nuclear material (SSAC) —organizational arrangements at the national level which may have both a national objective to account for and control nuclear material in the State and an international objective to provide the basis for the application of IAEA safeguards under an agreement between the State and the IAEA. IAEA Safeguards Glossary, 2001 Edition, para 3.33.

[5] Defense in Depth—An approach to designing and operating nuclear facilities that prevents and mitigates accidents intentional or otherwise that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. Defense in depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures. http://www.nrc.gov/reading-rm/basic-ref/glossary/defense-in-depth.html.

areas such as safety and physical security, it also plays a key role in NMAC. All of the functions required by an NMAC will vary from state to state, but in general, key elements include:

- maintaining an up-to-date inventory of all nuclear material present;
- record of all receipts, shipments, and losses/gains;
- on each item is:
  - unique identifier
  - location
  - isotopic composition
  - quantity
  - type of material
- access control to the facility and specific locations in the facility, as needed;
- initiate an alarm when specified measurement uncertainties are exceeded on items and mass balances, and when access controls are violated;
- identify the location of all alarms;
- in the case of missing nuclear materials, identify the specific items and their quantities and characteristics;
- assist in the timely resolution of any alarms; and
- provide the foundation for any investigation of serious events and for an emergency inventory to address potential missing items.

A comprehensive NMAC system should meet the goal of providing timely and accurate information on all nuclear material activities in the facility. Through this capability, it should deter and, if necessary, detect any unauthorized access and/or activities to nuclear material.

Program Management

Effective organization and management of an NMAC system provides greater assurance that the system is capable of detecting unauthorized removal of nuclear material. An effective program is also sustainable and requires controls to ensure any changes to the facility operation or equipment do not compromise or reduce the safeguards' effectiveness.

Organizational Structure

Within the facility, an NMAC manager will be assigned who will be responsible for implementing all programs associated with the accounting and control of all nuclear material at the facility. Ideally, the position of NMAC manager would be a full-time position, but for smaller and less complex facilities, the role of NMAC manager may be combined with other responsibilities. Similarly, the staffing level of an NMAC department can range from a very few personnel to over 30 personnel. However, one key aspect of the organizational structure is the separation of duties.

Separation of Duties

Separation of duties is used within systems to manage individual functions in order to reduce the opportunities for fraud and inadvertent actions that result in compromises, inappropriate authorizations, and illegal activity. The separation of duties principle reduces the extent of actions that can be performed by a single individual, and requires collusion to perpetrate intentional damage, fraud, and/or theft. In practice separation of duties is based on a risk assessment for each job category within a facility, where risk is reduced by limiting the span of control by any one individual.

First, the NMAC manager and NMAC department should be organizationally independent from operations or production departments. Regardless of the facility mission, the production or operations facility personnel will want to fulfill that mission as effectively as possible. Unless a strong nuclear security culture is present, given a conflict between an NMAC requirement and meeting the mission goal, the operations personnel may choose the mission goal, thus potentially compromising the security of the nuclear material. The NMAC manager must be in a position and have the authority to ensure that mission requirements do not compromise the security of the nuclear material and, if necessary, halt operations if such security programs are being compromised.

Secondly, the NMAC organization must be structured to ensure that security requirements cannot be compromised by an insider undetected, and effectively deter such attempts. For example, personnel responsible for implementing NMAC requirements, such as the NMAC manager, should not be able to handle the nuclear material. Similarly, work performed by those handling the nuclear material, such as taking measurements or completing transfers, should be checked by personnel responsible for NMAC before being included in the official accounting records.

Material Balance Areas

Another function of NMAC management is the establishment of material balance areas (MBAs) for the facility. An MBA is an area that is both a subsidiary account of materials at a facility and a single geographical area that has defined boundaries and is an integral operation. It is used to identify the location and quantity of nuclear materials in a facility[6] and is an area

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[6] DOE Standard DOE-STD—1194-2011.

designated such that (1) the quantity of nuclear material in each movement into and out of the area can be determined and is documented, and (2) the physical inventory of the nuclear material within can be determined when necessary.[7] Thus, on a periodic basis, the summation of what was in the MBA at the start of the period, plus the amount received into the MBA, minus the amount removed from the MBA, can be "balanced" against what is found in the area at the end of the period.

To meet the requirement of determining the quantity of material moving into and out of the MBA and what is physically present, each MBA will have defined key measurement points (KMPs) for the MBA. A KMP is a location where nuclear material appears in such a form that it may be measured to determine material flow or inventory. This includes, but is not limited to, the inputs and outputs (including measured discards) and holdings in MBAs.[8] KMPs will be included in the NMAC measurement control program (MCP) to ensure that they are periodically calibrated and that their measurement precision and accuracy meet NMAC requirements.

The number of MBAs that may be designated at a facility will vary widely based upon several factors, such as the geographical layout of the facility, the mission of the facility, the amount of nuclear material movements within the facility, and the quantity and number of nuclear material items in a given area. For example, in a research reactor facility where all of the nuclear material (e.g., fresh fuel, reactor core, and spent fuel) may be stored in the same building, a single MBA may be utilized (see Fig. 7.1). For more complex facilities such as an enrichment cascade, which could have multiple buildings for the enrichment process, several large storage lots or areas for feed, product, and by-product (depleted) materials, as well as decontamination and recovery buildings and an analytical laboratory, multiple MBAs may be utilized.

It is especially important that whatever MBA structure is chosen, it should be able to localize losses and gains, which can reflect off normal events in processing or potential theft. Consider a facility that has a number of unrelated and independent activities being carried out in a single building. One would expect the entire building or more to be the MBA. But this will not allow the localization of gains or losses. Some facility NMAC programs use sub-MBAs to address this issue. The sub-MBA now bounds each independent activity such that any gains or losses can be directly assigned to that specific activity. This allows for a rapid and efficient resolution process to resolve any unexpected gains and losses.

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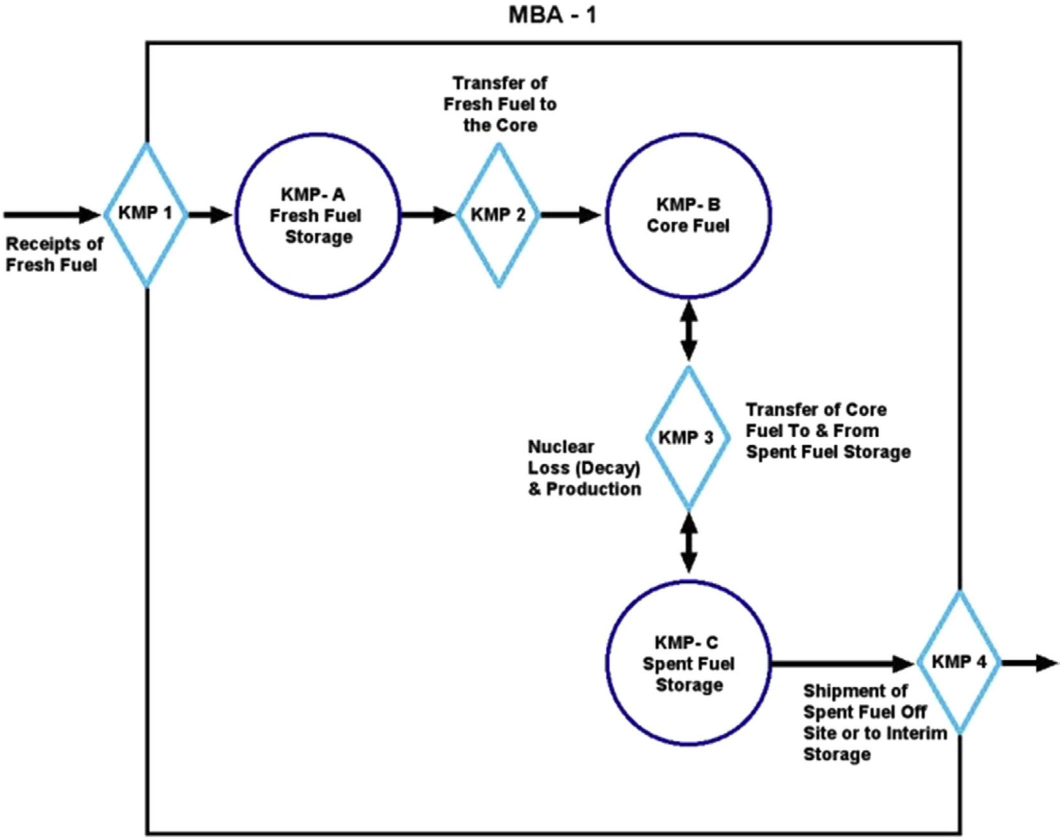
[7] International Atomic Energy Agency. Nuclear security series No. 25-G, *Use of nuclear material accounting and control for nuclear security purposes at facilities*, Vienna; 2015.

[8] DOE STD-1194-2011.



■ **FIGURE 7.1** Research Reactor MBA Structure.

It should be noted that the IAEA also requires reporting based on an MBA structure for the facility. However, that structure may not be the same as what the facility utilizes internally to localize inventory differences. The facility may choose to combine internal MBAs when reporting to the IAEA to minimize the reporting of movements in and out of the MBA. This provides some incentive for a state's NMAC system to minimize MBAs. The IAEA MBA structure for a facility is negotiated with the IAEA by the state when placing the facility under IAEA safeguards. In some cases (such as a reactor), the number of MBAs may be only one. In other more complex processing facilities, it may be more. However, regardless of the IAEA reporting structure, it does not preclude the facility NMAC system from using a more complex MBA/sub-MBA structure internally for the purposes of effective tracking of nuclear material.

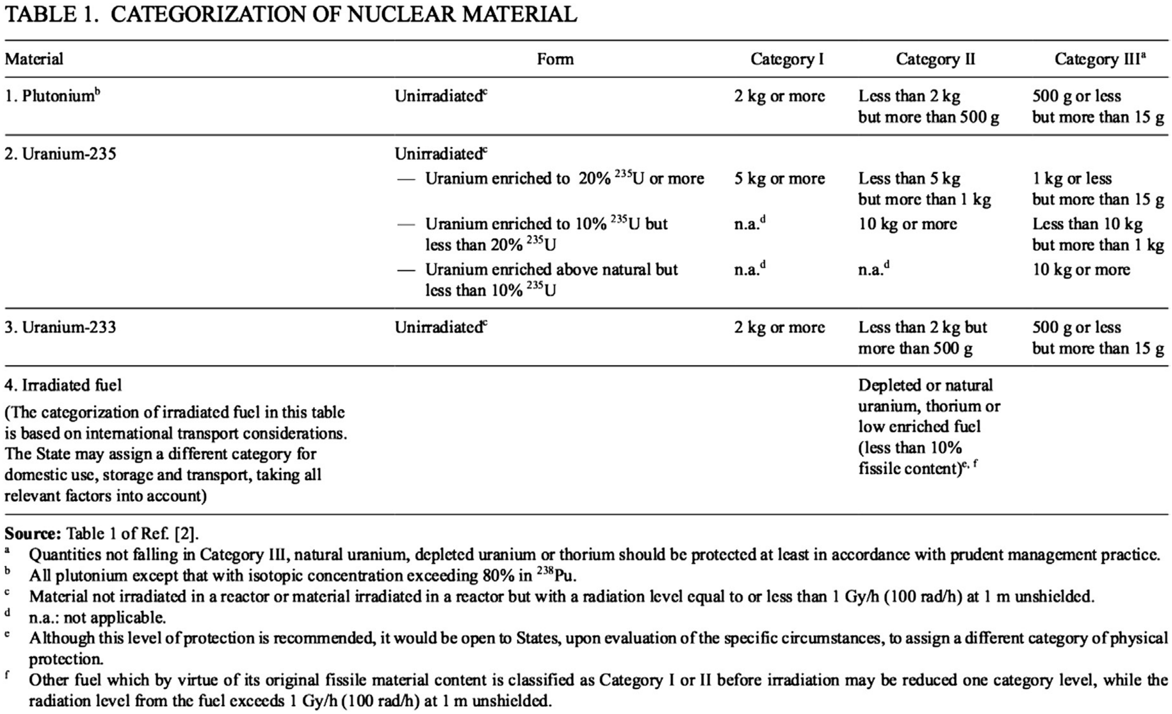


TABLE 1. CATEGORIZATION OF NUCLEAR MATERIAL

Material	Form	Category I	Category II	Category III[a]
1. Plutonium[b]	Unirradiated[c]	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
2. Uranium-235	Unirradiated[c]			
	— Uranium enriched to 20% ^{235}U or more	5 kg or more	Less than 5 kg but more than 1 kg	1 kg or less but more than 15 g
	— Uranium enriched to 10% ^{235}U but less than 20% ^{235}U	n.a.[d]	10 kg or more	Less than 10 kg but more than 1 kg
	— Uranium enriched above natural but less than 10% ^{235}U	n.a.[d]	n.a.[d]	10 kg or more
3. Uranium-233	Unirradiated[c]	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
4. Irradiated fuel (The categorization of irradiated fuel in this table is based on international transport considerations. The State may assign a different category for domestic use, storage and transport, taking all relevant factors into account)			Depleted or natural uranium, thorium or low enriched fuel (less than 10% fissile content)[e, f]	

Source: Table 1 of Ref. [2].

[a] Quantities not falling in Category III, natural uranium, depleted uranium or thorium should be protected at least in accordance with prudent management practice.

[b] All plutonium except that with isotopic concentration exceeding 80% in ^{238}Pu.

[c] Material not irradiated in a reactor or material irradiated in a reactor but with a radiation level equal to or less than 1 Gy/h (100 rad/h) at 1 m unshielded.

[d] n.a.: not applicable.

[e] Although this level of protection is recommended, it would be open to States, upon evaluation of the specific circumstances, to assign a different category of physical protection.

[f] Other fuel which by virtue of its original fissile material content is classified as Category I or II before irradiation may be reduced one category level, while the radiation level from the fuel exceeds 1 Gy/h (100 rad/h) at 1 m unshielded.

FIGURE 7.2 International Atomic Energy Agency (IAEA) categorization table.

Material Balance Area Categorization

For each MBA and the facility as a whole, the quantity and attractiveness of the nuclear material present will define the category of the MBA and/or facility. If under IAEA safeguards, the categorization of the facility and MBA used to establish inspection frequencies by the IAEA and to define various NMAC recommendations and other security recommendations are set forth in IAEA Nuclear Security Series documents.[9] The categorization used by the IAEA is defined within Nuclear Security Series No. 13 and is shown in Fig. 7.2.

As an example of how the state may define categorizations of facilities and MBAs, within the United States, there are two different regulatory bodies that define categorization differently from the IAEA and, in fact,

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[9] As opposed to a State established laws and orders, which may be used as a requirement for operation, IAEA Nuclear Security Series documents do not define requirements but only recommendations that the State and/or facility should implement to meet internationally accepted practices.

differently from each other. This unusual split between two regulatory bodies is a result of the United States being a nuclear weapons state where the material under the weapons program is segregated from all commercial activities. Commercial facilities are regulated under the Nuclear Regulatory Commission (NRC) and utilize the following categorization[10]:

Category I means strategic special nuclear material (SSNM)[11] in any combination in a quantity of

- 2 kgs or more of plutonium;
- 5 kgs or more of U-235 (contained in uranium enriched to 20% or more in the U-235 isotope);
- 2 kgs or more of U-233; or
- 5 kgs or more in any combination computed by the equation grams = (grams contained U-235) + 2.5 (grams U-233 + grams plutonium).

Category II, Special nuclear material of moderate strategic significance, means

- less than a formula quantity of strategic special nuclear material but more than 1000 g of uranium-235 (contained in uranium enriched to 20% or more in the U-235 isotope) or more than 500 g of uranium-233 or plutonium, or in a combined quantity of more than 1000 g when computed by the equation grams = (grams contained U-235) + 2 (grams U-233 + grams plutonium); or
- 10,000 g or more of uranium-235 (contained in uranium enriched to 10% or more but less than 20% in the U-235 isotope).

Category III, Special nuclear material of low strategic significance, means

- less than an amount of special nuclear material of moderate strategic significance (see Category II above) but more than 15 g of uranium-235 (contained in uranium enriched to 20% or more in U-235 isotope) or 15 g of uranium-233 or 15 g of plutonium or the combination of 15 g when computed by the equation grams = (grams contained U-235) + (grams plutonium) + (grams U-233);
- less than 10,000 g but more than 1000 g of uranium-235 (contained in uranium enriched to 10% or more but less than 20% in the U-235 isotope); or
- 10,000 g or more of uranium-235 (contained in uranium enriched above natural but less than 10% in the U-235 isotope).

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[10] United States Code of Federal Regulations, 10 CFR 74.4.

[11] Strategic special nuclear material means: Uranium-235 (contained in uranium enriched to 20% or more in the U-235 isotope), Uranium-233, or Plutonium.

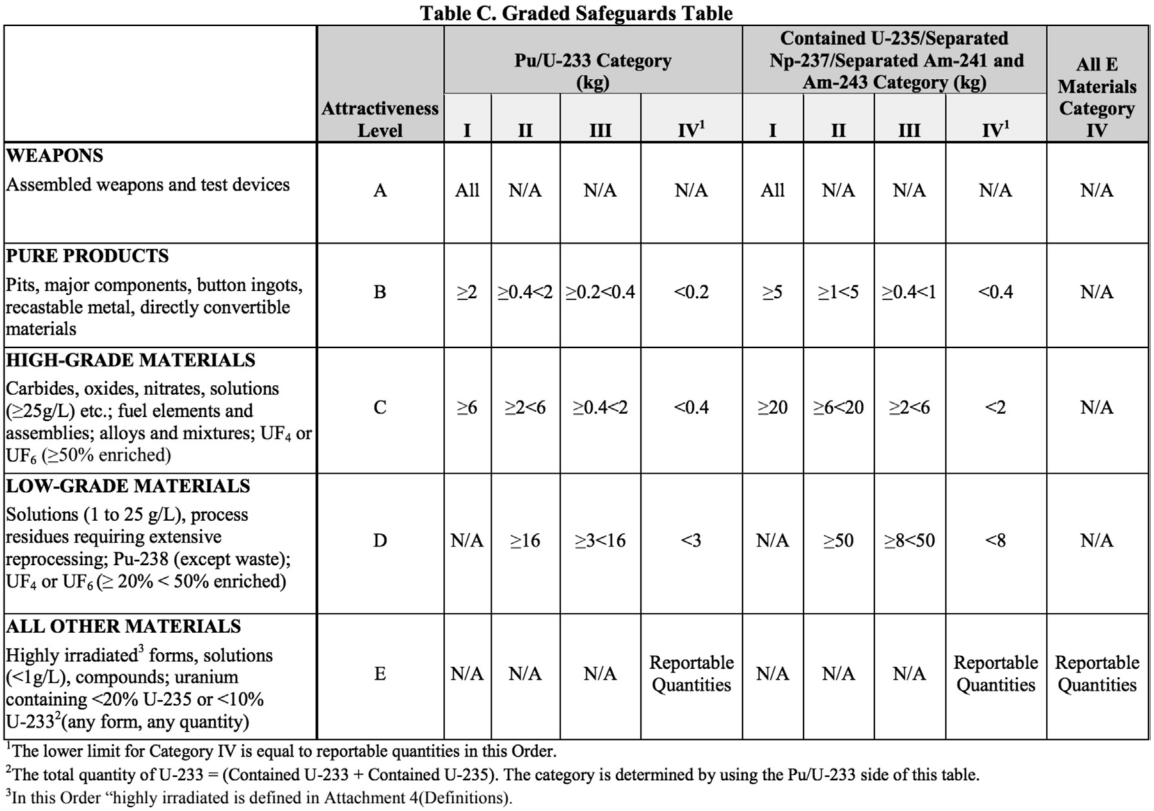

Table C. Graded Safeguards Table

	Attractiveness Level	Pu/U-233 Category (kg)				Contained U-235/Separated Np-237/Separated Am-241 and Am-243 Category (kg)				All E Materials Category IV
		I	II	III	IV[1]	I	II	III	IV[1]	
WEAPONS Assembled weapons and test devices	A	All	N/A	N/A	N/A	All	N/A	N/A	N/A	N/A
PURE PRODUCTS Pits, major components, button ingots, recastable metal, directly convertible materials	B	≥ 2	$\geq 0.4 < 2$	$\geq 0.2 < 0.4$	< 0.2	≥ 5	$\geq 1 < 5$	$\geq 0.4 < 1$	< 0.4	N/A
HIGH-GRADE MATERIALS Carbides, oxides, nitrates, solutions ($\geq$25g/L) etc.; fuel elements and assemblies; alloys and mixtures; UF$_4$ or UF$_6$ ($\geq$50% enriched)	C	≥ 6	$\geq 2 < 6$	$\geq 0.4 < 2$	< 0.4	≥ 20	$\geq 6 < 20$	$\geq 2 < 6$	< 2	N/A
LOW-GRADE MATERIALS Solutions (1 to 25 g/L), process residues requiring extensive reprocessing; Pu-238 (except waste); UF$_4$ or UF$_6$ ($\geq$ 20% < 50% enriched)	D	N/A	≥ 16	$\geq 3 < 16$	< 3	N/A	≥ 50	$\geq 8 < 50$	< 8	N/A
ALL OTHER MATERIALS Highly irradiated[3] forms, solutions (<1g/L), compounds; uranium containing <20% U-235 or <10% U-233[2](any form, any quantity)	E	N/A	N/A	N/A	Reportable Quantities	N/A	N/A	N/A	Reportable Quantities	Reportable Quantities

[1]The lower limit for Category IV is equal to reportable quantities in this Order.

[2]The total quantity of U-233 = (Contained U-233 + Contained U-235). The category is determined by using the Pu/U-233 side of this table.

[3]In this Order "highly irradiated is defined in Attachment 4(Definitions).

■ **FIGURE 7.3** US Department of Energy categorization table.

Facilities that are regulated by the US Department of Energy (US DOE) utilize a different set of criteria for determining the category of the facility or MBA. Unlike the IAEA and US NRC, which only look at whether the material is U^{235} and its enrichment, U^{233} or Pu, and then the quantity, US DOE looks at these attributes as well as other criteria for attractiveness level. US DOE defines attractiveness level as the grouping of special nuclear material types and compositions that reflects the relative ease of processing and handling required to convert that material to a nuclear explosive device.[12] Once the attractiveness level of the material is determined, then the total quantity of that material is used to define the category level. Fig. 7.3 shows the US DOE table used to determine the category of the MBA and/or facility.

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[12] Department of Energy Order 474.2 Change 2. *Nuclear material control and accountability, DOE*; 2012.

As mentioned, the categorization of the MBA is used not only to define various physical protection requirements and/or recommendations but also NMAC requirements and/or recommendations. Category I MBAs/facilities will require a higher level of physical protection and a more stringent NMAC program (i.e., shorter inventory frequencies stricter access controls, etc.) to detect a possible theft or misuse of material. Similarly, Category II MBAs/facilities will require more than Category III or IV MBAs/facilities. This concept, known as a graded approach, allows resources to be focused on the more desirable adversary target. The role of the NMAC management is to both determine the category level for the facility and each MBA and to ensure resources are adequately appropriated to meet the State's requirements.

When categorizing a facility or area within a facility, the concept of roll-up must also be considered. Roll-up is defined as the accumulation of lower-category quantities of special nuclear material to a higher-category quantity, either from within one location or from more than one location within a single security area.[13] For example, if a facility has several MBAs that are each Category III MBAs, but their aggregate nuclear material quantity sums to a Category I quantity, the facility must protect the areas as a Category I area unless it can demonstrate that it is not credible for an adversary to accumulate a Category I before detection. Separation of duties and limiting access (to only those assigned to the various MBAs) are ways that are typically used to mitigate roll-up. It should also be noted that roll-up must be considered when transporting multiple lower-category items in the same shipment to ensure that the total for the shipment does not accumulate to a higher category level without also increasing the physical protection commensurate with that higher level.

Plans and Procedures

Another important component of the NMAC management is the development of plans and procedures to address NMAC program element implementation. The facility's key document in the NMAC program is the NMAC plan. Its primary function is to describe to the regulatory body how the facilities NMAC programs will be operating to meet the regulatory requirements. In many cases, this document will serve as one basis for operation of the facility. For example, facilities regulated by US NRC must submit a fundamental nuclear material control and accountability plan to the US NRC for approval prior to obtaining a license to operate. The US NRC will review and decide if when implemented by the facility, the facility will meet the intent of the US NRC regulations.

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[13] DOE Glossary of terms.

The next level of documents are procedures, which take the programs defined in the NMAC plan and further define who is responsible for performing the function, how that function will be performed, and how the completion of that function is documented. These procedures are not limited to NMAC personnel. Personnel who transport, handle, or measure nuclear material or calibrate NMAC instrumentation also play a role in the NMAC process and thus must have applicable procedures to ensure their functions are performed consistently each time. Typically, the NMAC management program will require that all such procedures be reviewed and approved by the NMAC manager.

In reviewing the NMAC plan and procedures, the NMAC manager is looking to ensure that the all requirements defined by the State are correctly applied to a facility procedure, which defines who is responsible for meeting and documenting that requirement. For example, the state may require that scales be checked for operability every shift that it is used to measure nuclear material; the NMAC plan may define how the production personnel are responsible to check the scale each shift prior to use, and the production scale operating procedure defines that the scale operator will check the operability of the scale by putting a known weight on the scale prior to use and ensuring that the scale reads within expected tolerance, and then records the check weighing in a logbook. Thus, when the regulator conducts an inspection, the facility can show that they are meeting the requirement by providing the record of the check weighing from the logbook.

Training and Qualifications

Similar to procedures, the NMAC manager is responsible for ensuring all personnel with NMAC responsibilities are properly trained and qualified to perform their assigned functions. The NMAC training and qualifications program will typically be documented in the NMAC plan and include identifying NMAC positions and defining minimum qualification for each position and any requalification criteria. This will include, but is not limited to, personnel within the NMAC organization and those involved in taking NMAC measurements, conducting inventories, applying tamper-indicating devices (TIDs), handling nuclear material, and any other function that has direct application to NMAC elements.

In many cases, the NMAC organization will develop specific training to be used by production personnel, measurement personnel, security personnel, and others to ensure that the importance of NMAC is conveyed and that the NMAC requirements are consistently being implemented. Training materials and plans are reviewed periodically to ensure they are current with the NMAC functional responsibilities.

Configuration Management

The NMAC manager is also responsible for ensuring that any proposed change to facility operations is reviewed to ensure that its implementation would not degrade the safeguards or security of the nuclear material. Since the NMAC plan is such a key component to the implementation of the NMAC program in meeting the requirements, it is essential that any procedural change be reviewed against the current plan and the plan amended, if necessary. Changes or purchasing of new measurement equipment should also be approved and documented through the NMAC organization to ensure the new equipment would still meet accuracies and precision requirements defined in the NMAC plan.

In some cases, the State may require that any change in what is documented in the NMAC plan be preapproved by the regulatory body before being implemented. In other cases, the state may require only those changes that reduce the safeguards' effectiveness be preapproved before implementation. Regardless of the State's requirement, the NMAC plan should define how changes are reviewed, approved, and documented and, if necessary, how and when the plan is amended.

Accounting Records and Reports

Nuclear material accounting refers to "activities carried out to establish the quantities of nuclear material present within defined areas and the changes to those quantities within defined periods."[14] This section will focus on the accounting records and reports necessary for tracking nuclear materials from not only the state and/or international perspective but also from the facility perspective. Accounting activities such as measurements, transfers, and inventory taking are discussed in more detail in later sections.

Introduction

Although there may be various levels and purposes of accounting for nuclear material, they all strive for the same basic goal of knowing how much material is present and where that material is located so as to ensure that nuclear material has not been stolen or misused undetected. From an IAEA safeguards perspective, the use of nuclear material accounting and facility inspections is focused on detecting missing nuclear materials and/or undeclared activities by the facility and/or state. From the state and/or facility level, nuclear material accounting is used not only to meet IAEA safeguards reporting requirements (if placed under IAEA safeguards) but also to detect potential theft of nuclear materials. The accounting records

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[14] *IAEA safeguards glossary*, Vienna; 2001.

also provide a means for assessing the performance of the NMAC system and determining compliance with a State's regulatory requirements.[15]

In many aspects, nuclear material accounting is no different than financial accounting in that generally accepted accounting principles are used in recording transactions and changes. Just as money is tracked from financial institute to financial institute and account to account, so is nuclear material tracked from facility to facility and MBA to MBA. Similarly, for both financial and nuclear material accounting, the holdings in each account can be determined by summing the amount started with plus the amount added minus the amount removed.

Accounting Records

Each time nuclear material is received, moved, processed, measured, and/or shipped, a nuclear material accounting transaction is generated. These transactions are collected in the nuclear material accounting ledger or system (either manually or computerized) and provide the basis for tracking the nuclear material quantities in each facility/MBA. Each transaction will have a unique identifying number for the item or batch, and include such information as MBA/facility involved in the transaction, quantities (including net, element, and isotope weights), and type of nuclear material involved, type (receipt, shipment, blending, etc.) and date of transaction, and some mechanism to track the personnel responsible for performing the transaction. Additional information, such as measurement method used and its uncertainty, tamper indicating device (TID) applied, and specific location of the item[16] within the MBA, may also be applicable.

The time frame for updating the ledger after each transaction will vary based on the State's regulations and facility operation but will be defined in the NMAC plan. One of the essential purposes for the accounting records is to provide a near real-time listing of the material that should be present in the MBA or facility should an emergency or security event require validation that nothing has been stolen or diverted.

A checks-and-balances system will also be used by the facility for inputting data into the accounting records. In some cases, source documents, such as waybills, weight tickets, laboratory results, etc., may be submitted to the NMAC personnel, and the NMAC personnel will then update the accounting records. In other cases, personnel performing the activity may document the transaction in a pending file until the accounting personnel can validate

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[15] DOE STD-1194-2011.

[16] The level of detail for location may vary based on regulatory requirements but should be specific enough to provide for retrieval of the item in a timely manner.

the information. In either case, the goal in the checks-and-balances system is to ensure that no single person can falsify records to conceal theft of material such that it remains undetected. Similarly, all transactions are permanently retained. If an error in recording the transaction is detected (i.e., transposition of a weight or item number), the transaction is not deleted from the ledger, but rather an additional adjustment transaction will be put in the ledger to correct the error.

As mentioned, information in the facility accounting ledger will be used to track material received, processed, and shipped from each MBA. Furthermore, depending on the facility, the ledger may also be used to track material types or forms. For example, in a uranium enrichment cascade, the ledger would not only track material by MBAs but also by enrichment-level ranges.[17] Electronic ledgers can also be used to track the timeliness of completing internal transfers. Where nuclear material is moved between MBAs and/or sub-MBAs, a time limit can be established from the time the material leaves the MBA/sub-MBA to when it is received at the other MBA/sub-MBA such that when that time limit is exceeded, an alarm is triggered, requiring NMAC staff to investigate the delay.

Accounting Reports

There are numerous types of reports that the accounting system can generate, but the three primary reports used are the (1) physical inventory listing (PIL), (2) inventory change report (ICR), and (3) material balance report (MBR).[18]

PIL is a report in connection with the physical inventory taking (PIT), listing all items and batches separately and specifying material identification and data for each item/batch that is present.[19] The PIL serves as a declaration of the material present and can used by regulatory authorities and if under IAEA safeguards, the IAEA, to validate the book versus the physical inventory as described by the facility NMAC program.

ICR is a report that documents all the transactions associated with the MBA. This includes not only the receipt and shipment of material but also changes that may have occurred to do processes (i.e., enrichment changes, remeasurements, material put in the process or removed, etc.).

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[17] As a minimum, enrichment facilities will have at least three ranges: depleted, natural, and enriched. Facilities that have higher than 10% U^{235} will also have ranges from 10% to 20% enriched and above 20% and possibly more.

[18] Different names may be used for each of these reports but the essence behind them does not change.

[19] IAEA Glossary.

MBR is the compilation of all of the records associated with the MBA over the inventory period. The MBR includes the physical inventories taken at the beginning of the inventory period (which is the same as the physical inventory taken at the end of the previous inventory period) and the changes to the inventory over the inventory period, and it calculates the "book ending" inventory or the amount of material that should be in the MBA. The MBR also lists the PIT at the end of the inventory and the difference between the book ending inventory and ending physical inventory known as the material unaccounted for (MUF). Another term for this difference between the book and physical inventory is known inventory difference (ID). Note that for item MBAs, the book and physical ending inventories should be identical, but for processing MBAs, they will not be the same because of measurement uncertainty. This is discussed in later sections of this chapter.

Although the PIL, ICR, and MBR are generated for each MBA, it is not uncommon for the MBAs to be combined and generate facility-level reports as well. Similarly, states with facilities under IAEA safeguards may choose to combine all or part of the facility MBAs into specific reporting entities to minimize the number of reports given the IAEA inspectorate. In these cases, transfers between MBAs with the entities would be ignored and only those transfers in and out of the combined MBAs reported.

Nuclear Material Measurements in Support of Nuclear Material Accounting and Control

The ability to measure nuclear material is of fundamental importance not only to the NMAC system required by the SRA but also in meeting the needs of the state to assure public safety, to protect the economic investment, to provide the basis for criticality safety within a facility, and to meet international obligations such as for regional agreements and for the IAEA. The measurement and sampling techniques shown in the following pages are only representative of a small segment of commercially available products and are not endorsements of these products. A much wider range of techniques is available, and readers interested in this area will find many of the references a good source for more detailed information.

Introduction

These measurements can be qualitative and/or quantitative. While there is no fixed definition for nature of or the terms used for each type, a qualitative measurement, for example, gives a yes/no answer on the detection of a radioactive element(s). These are sometimes referred to as an attribute[20] or

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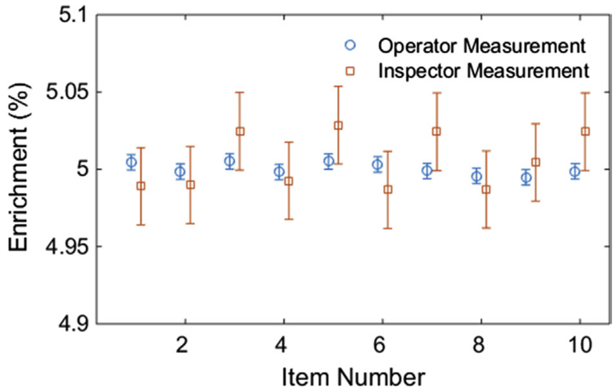
[20] 10.30. Attributes test: A statistical test of a characteristic (or attribute) of an item to which the response is either 'yes' or 'no'. IAEA safeguards glossary 2001 edition, International nuclear verification series no. three.

confirmatory measurement. For an individual item, the attribute might be the radioactive signal identifying the presence of uranium or plutonium. A quantitative measurement, as its name implies, will quantify some aspect of the material being measured. Examples might be the mass and/or isotopes of an element. Unlike a qualitative measurement, a quantitative measurement will also have an uncertainty associated with the quantity measured. As with qualitative, terms can vary, but for an individual item, quantitative measurement for NMAC might be referred to as accountability or verification measurements.

There is an important distinction between accountability versus verification measurements. Accountability measurements are performed by a facility operator to establish the nuclear material value of an item(s) as recorded in the NMAC system. The facility operator must be able to defend this quantity based on the measurement system used, calibration of the measurement system, calibration standards, and the measurement control program (MCP), assuring it is in control at the time of the measurement. These aspects will be discussed later in this section. The operator's measurements are normally of higher quality than any done by an inspectorate and are typically based on destructive assay techniques that have the smallest measurement uncertainty. These measurements are more accurate than those typically required by NMAC program but are needed to meet product quality control requirements. When a facility receives material, such a reactor receiving fresh fuel, the accountability values will be based on the shipper's values, as they manufactured the fuel assemblies. A source document from the shipper will be transmitted to the receiving facility to support the nuclear material value entered in their accountability records. The basis for accepting a shipper's nuclear material value is defined in the shipper/receiver agreement and often reflects either the inability of the shipper to measure an item, such as a fuel assembly, or that the receiver's measurement uncertainty is larger than the shipper's. This supports the focus on maintaining the most accurate values available on nuclear materials.

A verification measurement maybe performed by an inspectorate to verify the operator's declaration of the item's nuclear material content as indicated in the operator's book inventory listing. Although verification measurements will provide a quantitative result, it is typically not, as previously mentioned, as accurate as the accountability measurement previously used. Thus, a verification measurement is typically not used to change the accounting value for the item unless it is shown to be of equal or greater in precision and/or accuracy. Since both are quantitative measurements, they also have an uncertainty associated with the quantity measured. This statistical variation is shown in Fig. 7.19 and as a result, repeat measurement on the same item will be expected to vary based on the associated uncertainty of the measurement technique in its operational environment,



■ **FIGURE 7.4** Notional comparison of operator and inspector measurements.

and this does include remeasurement using the identical technique under identical conditions. Therefore, determining whether an individual verification measurement passes is based on a statistical evaluation to determine if the difference between the quantity measured and the quantity declared falls within the expected measurement uncertainty of the two techniques used by the inspector and operator. It is also common for an operator to remeasure inventory items, and the statistical evaluation is again a key determination of whether the two measurements agree within the measurement uncertainty of the same technique applied again. It is also typical that the operator's measurement uncertainty is better than the inspector, since more accurate techniques, such as destructive assay (DA), are used, whereas the inspectorate typically relies on more rapid in-field techniques, such as nondestructive assay (NDA), that are not as accurate. An example of measurements taken by both parties is shown in Fig. 7.4.[21] While there may be a number of reasons for an operator to remeasure an item, including when an instrument fails a measurement control test or for quality assurance purposes. In fact, such remeasurements are a key component of a strong the measurement quality control program, as discussed in Measurement Quality Control Program section.

In this figure, while each measurement of the enrichment is different, because the expected uncertainty range (indicated by the T-bars on each measurement point) of each measurement overlaps, this indicates that the difference can be accounted for solely due to measurement error.

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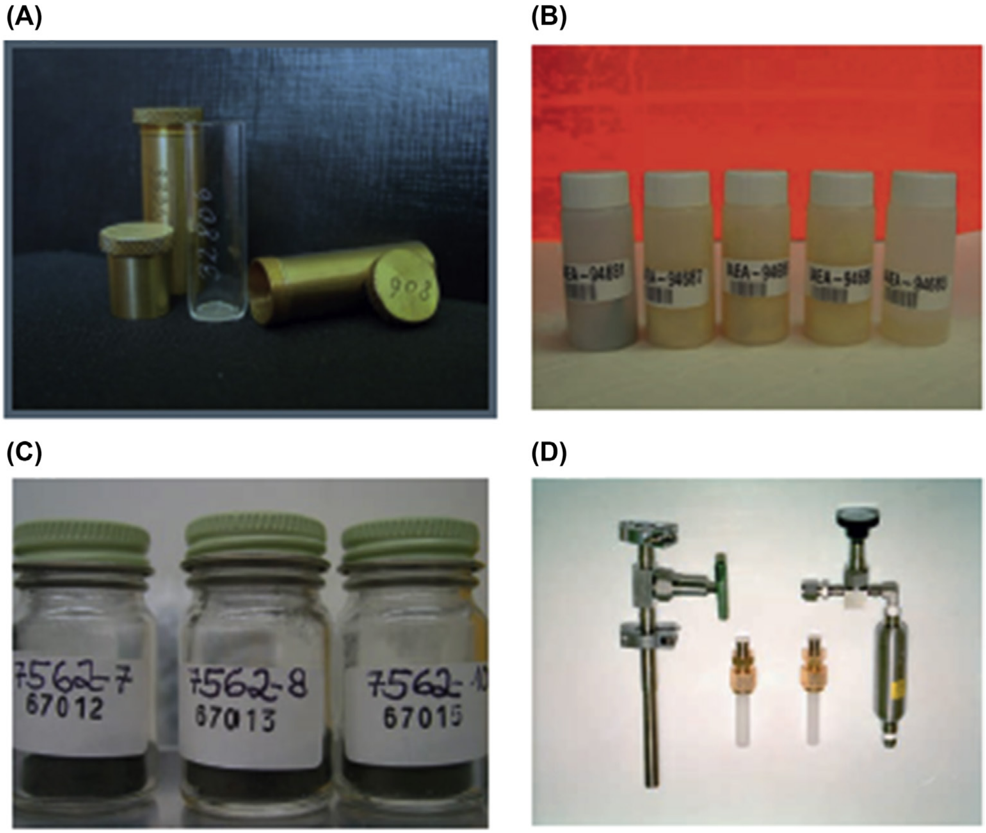
[21] Nonproliferation Portal, 4.3.5. Verification of operator's measurement systems, K. Jarman, PNNL. https://www.nonproliferationportal.com/.



■ **FIGURE 7.5** Examples of various sample bottles: (A) plutonium, MOX, or highly enriched uranium (HEU) powder, (B) solid materials, (C) DU, NU, or low enriched uranium (LEU) powders, and (D) UF6 gas sample bottles. DU, depleted uranium (uranium with an enrichment less that what is found in nature <0.711%); MOX, mixed oxide (contains both Pu and U); NU, uranium which has not gone through any enriching process and is at it's nature enrichment of 0.711%).

Types of Measurements[22]

There are two basic types of measurement techniques used to measure nuclear material: DA and NDA. In DA, a representative sample of nuclear material is taken from a bulk item or process (see Fig. 7.5).[23] The ability to obtain a representative sample is a key consideration for whether DA can be used for accountability purposes. This sample must be representative of all the material present, so the item being sampled must be homogeneous.

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[22] Note: The reader should keep in mind that the instrumentation and technologies discussed here rapidly change over time. Everything mentioned should be considered only as representative of the field and not inclusive.

[23] *IAEA safeguards techniques and equipment: 2011 edition, International nuclear verification series no. 1 (rev. 2)*; p. 86.

Table 7.1 Examples of Primary Analytical Techniques

Analytical Technique	Analyzed for	Type of Material	Uncertainty (% Rel.)	
			Random	Systematic
Elemental Analysis				
Alpha spectrometry	Np, Am, Cm	High active liquid waste (HALW), spent fuel input	5.0	5.0
Controlled potential coulometry	Pu	Pure Pu solutions	0.10	0.10
Ignition gravimetry	U, Pu	U, Pu oxides	0.05	0.05
Isotopic dilution mass spectrometry (IDMS)	U, Pu	Spent fuel input solutions. Pu and U–Pu materials, HALW	0.20	0.20
Hybrid K-edge densitometry (HKED)	U, U:Pu ratio	Spent fuel solutions	0.60	0.30
K-edge densitometry (KEDG)	U, U:Pu ratio	U, U–Pu solutions	0.20	0.15
New Brunswick Laboratory Davies and Gray titration	U	U (pure compounds)	0.10	0.05
Plutonium (VI) spectrophotometry	Pu	Pu process solutions	2.0	2.0
Isotopic Analysis				
Alpha spectrometry	^{238}Pu	Pu materials	0.2	0.3
Gamma-ray spectrometry (NaI detector)	^{235}U	Low enriched U materials	0.3	0.3
High-resolution γ-ray spectrometry (Ge detector)	Pu isotopes, Am, Np	Pure U and Pu materials	0.5–2.0	0.5–2.0
Thermal ionization mass spectrometry (TIMS)	U and Pu isotopes	All Pu and U materials and spent fuel input solutions	0.10[a]	0.05[a]

At the analytical laboratory, that sample will typically go through some sample preparation where potential nonessential elements that might cause measurement interferences in the applied techniques are removed. The sample is then consumed as part of the analysis. Typically, an archive sample is also retained to support any future needs to defend the results and/or used as a redundant sample to support the quality assurance program. There are a number of techniques that focus on elemental and isotopic analysis (see Table 7.1).[25] It is not the intent of this section to go into details on the basis for each technique, as this is readily available in the open literature.[24] The selection of the technique will be based on what is being analyzed, the form of the material, and the desired uncertainty of the measurement determination. Some of these

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[25] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; p. 87.

[24] IAEA STR-369. *International target values 2010 for measurement uncertainties in safeguarding nuclear material*; November 2010 provides a good source for the various measurement techniques used on nuclear material and target measurement uncertainties.

measurement determinations for operator product are often defined by quality assurance requirements to meet a customer's specifications. These specifications can be far more stringent than those required by the NMAC system.

One example technique is a mass spectrometer. A specific isotope(s) can be isolated using this sensitive technique. Since different isotopes of an element have the same chemistry, another principle of physics is needed to separate the isotopes. That distinguishing principle is their different mass due to additional neutrons in the nucleus. Most importantly, along with different mass comes different nuclear properties such as the ability to fission. Knowing the isotopic composition then determines, for example, whether uranium is low enriched, highly enriched, or weapons grade. Similarly for plutonium, is it weapons grade, reactor grade, or can it be exempted from international safeguards due to a Pu238 isotopic composition equal to or greater than 80%? Fig. 7.6[26,27,28] shows three views on how a mass spectrometer works and a commercial unit. View (A) is an analogy using masses dropping from a building with a wind (representing a magnetic field) deflecting the lighter mass object further. The second, View (B), is a simplified drawing of the instrument showing how a particle is ionized and accelerated through a curved magnetic field to separate isotopes by mass with a collector at the end to count the number of events that relate to atoms collected. The third, View (C), is a picture of a Triton mass spectrometer. Newer mass spectrometers will have multiple collectors at different locations to assay many isotopes at once.

With these DA results and another bulk technique, such as weighing and/or liquid level/density, to determine the mass of the material to be accounted for, an accountability value can be determined where the total uncertainty is a combination of the techniques used. For example, to determine the mass of ^{235}U, that is in uranium oxide loaded into a container, the operator will first measure the weight of the oxide added to get a net weight of the oxide. Because there may be impurities present, the operator will extract a representative sample and the perform DA on the sample—first for concentration of the total amount of uranium (percent of the oxide that is U) and then the enrichment (percent of the U that is ^{235}U). Thus, the total uncertainty for how much ^{235}U is in the container will include the uncertainties associated with measuring (1) the net weight, (2) the homogeneity of the sample, (3) the measurement for uranium concentration, and (4) the measurement of the enrichment. How these uncertainties are combined is a complex process and typically requires a trained statistician to determine.

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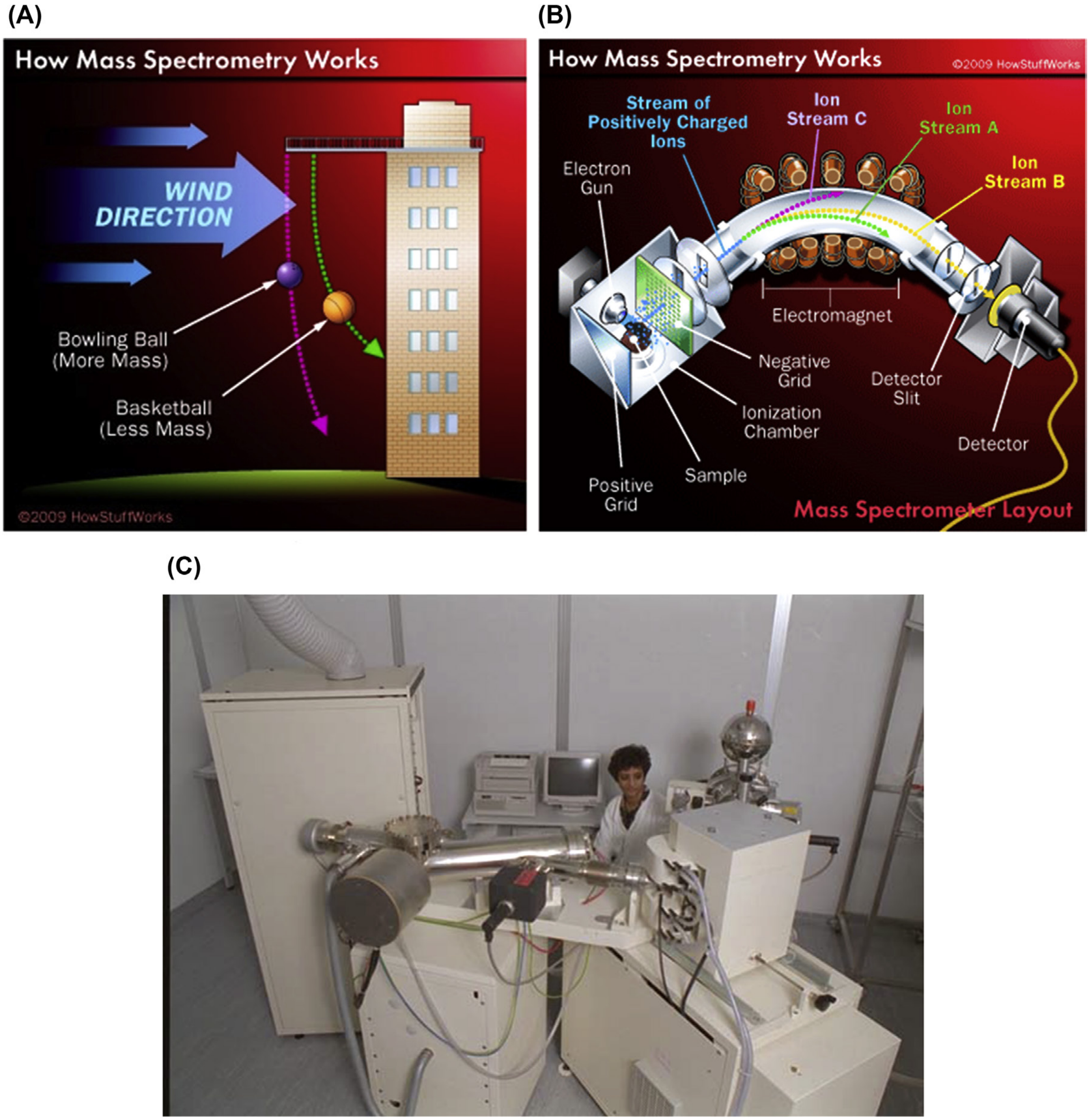
[26] http://science.howstuffworks.com/mass-spectrometry2.htm.

[27] IAEA Safeguards Analytical Laboratory. *Advanced sensors for safeguards, Santa Fe, NM, 2007-04-23 to 2007-04-27.*

[28] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series No. 1 (Rev. 2)*; p. 93.



■ **FIGURE 7.6** Thermal ionization mass spectrometer.

DA measurements typically provide a measurement with the best accuracy, but they are time-consuming and expensive in comparison to NDA measurements that are often less accurate, assay the entire item, and can be done quickly and at low cost. So understanding the nature of the material to be assayed, time and money available, and the uncertainty required to meet the measurement requirements all play a key role in determining what type of measurement should be applied. Also, as mentioned performing a DA requires a representative sample being removed from the item or batch. In many cases this means that product material is being removed and thus there is a cost for the loss of the material. Similarly, the DA will produce various contaminated waste that must be measured, accounted for and disposed. Finally, there are varying health and safety issues with drawing such a sample. All these factors must be weighed when determining whether to use DA or NDA to obtain a value for the item.

Historically, DA was the first type of measurements established for nuclear material. As the use of nuclear material expanded as part of the NFC for the generation of electricity and ongoing research, concerns arose over the potential for diversion by a state, theft, and terrorism. This prompted a need for less intrusive and safer techniques that could address the ability to measure nuclear material in all the forms found in the NFC, including heterogeneous forms such as residues and waste. Some of the early research to use the gamma-ray and neutron emissions from nuclear material for the purposes of safeguards started in the late 1960s at Los Alamos Scientific Laboratory (now called Los Alamos National Laboratory) under the leadership of G. Robert Keepin. Other technologies, such as calorimetry for the quantitative measurement of heat, were also developed to provide a very accurate measurement of nuclear material, such as plutonium, as long as the isotopic composition was known. A number of excellent references are available from multiple sources.[29,30]

We will start with techniques used on nonirradiated materials. Because of the unique energy nature of gamma-ray emissions from the nucleus of atoms, they can be used to identify specific isotopes of elements. This common application is called gamma-ray spectroscopy. The range of instruments available for such measurements varies widely based on the intended use and cost. For example, where very pure materials like uranium and plutonium are used, it is possible to use a low-resolution detector if one wants to simply identify the presence of these elements, whereas if an accurate determination of the percentage of each isotope in the element is needed, then a high-resolution unit can be used. The key is the ability of the detector to resolve gamma-ray peaks that are needed for the analysis.

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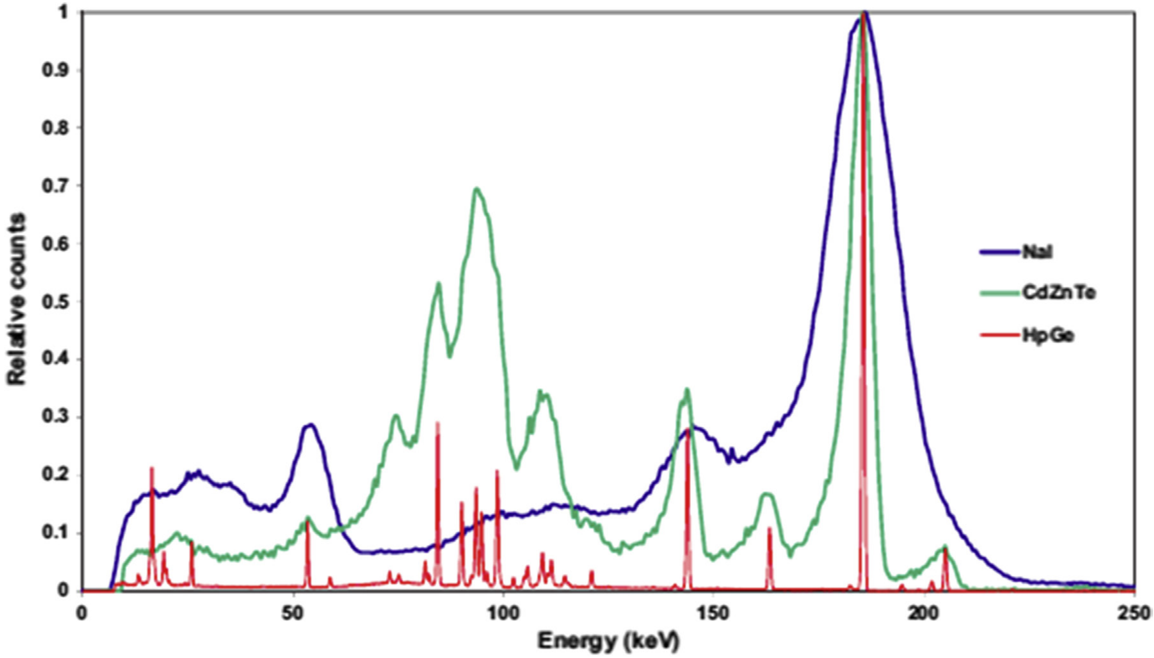
[29] Reilly D, Ensslin N, Smith Jr H, editors. *Passive nondestructive assay of nuclear materials*. Prepared for Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission; 1991.

[30] Knoll GF. *Radiation detection and measurement*. 4th ed.; August 2010.



■ **FIGURE 7.7** Comparison of resolution of NaI, CdZnTe, and high-purity GE (HPGe) detectors. *Reproduced with permission from: International Atomic Energy Agency, Safeguards Techniques and Equipment, International Nuclear Verification Series No. 1 (Rev. 2), IAEA, Vienna (2012).*

These measurements are typically on the order of minutes for completion. Fig. 7.7[31] shows the difference in resolving power for detectors of different resolution.

The legend in Fig. 7.7 starts with a low-resolution NaI detector, indicated in blue, ending with a high-resolution detector using high-purity Ge (HPGe), indicated in red. You can easily see how the high-resolution HPGe easily resolves many peaks that the low-resolution NaI cannot. Each peak can be related to a specific isotope or isotopes, and gamma-ray libraries are available to enable the identification of these isotopes. The following are examples of some gamma-ray measurement equipment used in the nuclear industry. Some of these instruments are used by inspectors, some by operators, and some by both. The decision on what is used by the inspectorate is determined by the NMAC regulator and would be based on many factors, including the confidence needed to satisfy inspection conclusions.

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[31] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; p. 9.

■ **FIGURE 7.8** HM-5 Hand Monitor, version five. *Reproduced with permission from: International Atomic Energy Agency, Safeguards Techniques and Equipment, International Nuclear Verification Series No. 1 (Rev. 2), IAEA, Vienna (2012).*

The FLIR HM-5 shown in Fig. 7.8[32] is a versatile NaI-based portable unit. It includes dose rate capability for safety of the user, find features for those trying to locate a gamma-ray source, a library of primary gamma-ray peaks for a wide assortment of radioisotopes to identify the gamma-ray source, an algorithm to calculate uranium enrichment, and many more features. This particular unit was originally designed for the IAEA, and the generic unit with similar capabilities is known as the IdentiFINDER. This unit can also have a small He3 tube for detection of neutrons. The basic HM-5 price range was ~$25,000 USD and the IdentiFINDER was ~$5,000 USD in 2016.

An example of a HPGe is the Ortec Detective shown in Fig. 7.9.[33] To obtain the excellent resolution of this detector requires cooling down to –160°C. This temperature was typically reached by use of liquid nitrogen in an attached Dewar. Recent advancements have resulted in the use of electrical cooling to make this an easily portable unit. The basic price range was ~$100,000 USD in 2016.

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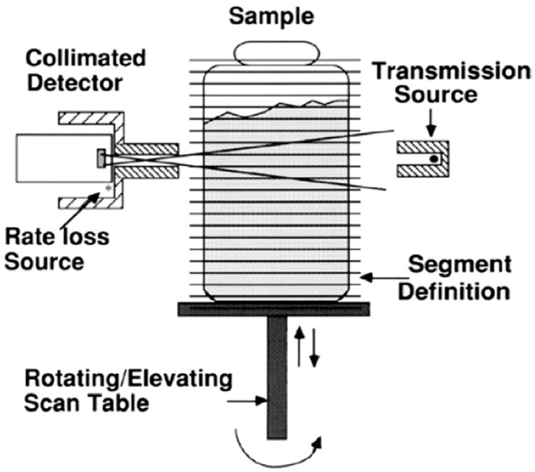
[32] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; p. 12.

[33] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; p. 14.

■ **FIGURE 7.9** Ortec detective high-purity GE (HPGe). *Reproduced with permission from: International Atomic Energy Agency, Safeguards Techniques and Equipment, International Nuclear Verification Series No. 1 (Rev. 2), IAEA, Vienna (2012).*

Besides spectroscopy, gamma-ray measurement can be used to quantify nuclear material in the right type of matrix. Because of the very high density of nuclear materials, in a solid form, gamma rays can be absorbed after a very short distance within the nuclear material. This is often referred to as the infinite thickness. For example, if you had uranium or plutonium in the form of a metal, most of the gamma rays emitted from deeper than 2 mm from the surface would be absorbed by the material they were passing through and not exit the material. Another way to state this is that the peak height or counts collected for these measured gamma rays would not increase once the thickness goes beyond 2 mm. So for dense matrices like metal or oxide (infinite thickness will vary depending on the density), you are only measuring the surface gamma rays. In this circumstance, the gamma-ray analysis is only applicable for the identification of the element, enrichment of uranium, and spectroscopy. However, where the matrix is low density, such as low-density wastes like rubber gloves and cleaning cloths that are contaminated with uranium and/or plutonium particles, it is possible to perform a quantitative measurement since there is very little self-absorption. What absorption there is can be calculated using a known penetrating gamma-ray source called a transmission source, measured through the matrix to calculate a correction factor. This source will be at a gamma-ray energy close to the gamma-ray peak used for the measurement of the isotope of interest since gamma rays of different energy have different penetrating power in a matrix. The closer the transmission source energy is to the gamma ray of interest, the more accurate the correction factor. One common gamma-ray instrument used to measure low-density waste is a segmented gamma scanner.



■ **FIGURE 7.10** Segmented gamma scanner components.

The segmentation refers to the incremental measurements made on multiple segments of the item as it is raised and rotated that are then summed to determine the total quantity of the nuclear material of interest.

Fig. 7.10[34] shows a drawing of the basic features of a segmented gamma scanner (SGS).

Fig. 7.11[35] is a picture of a commercial product developed by Canberra Industries, Inc. On the lower right side, you can see the liquid nitrogen Dewar attached to the HPGe detector. On the left side at the same level, you can see the shielded container holding the transmission source. Both detector and source are elevated through the segments covering the entire drum as it rotates on the scan table.

Some nuclear materials also emit neutrons, but unlike gamma rays, their energies are broad and can change based on interactions with matter, and, in addition, neutron detectors often do not measure the specific energy of neutrons. Nevertheless, the ability to count neutrons accurately in time can provide quantitative information of particular isotopes as long as the isotopic composition is also known. Because neutrons are so penetrating, unlike gamma rays, they can typically represent all of the material present even in a dense item. Where there is a high spontaneous neutron emission rate such as with plutonium, passive neutron counting can be used. Where the neutron rate is low as with uranium, active neutron interrogation is used to induce fission neutrons in ^{235}U. These measurements take on the order of tens of minutes for a complete assay.

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[34] Los Alamos National Laboratory. *Application note, segmented gamma-ray scanner*; March 1991.

[35] CANBERRA's WM2200 Segmented Assay System.

■ **FIGURE 7.11** Canberra segmented gamma-ray scanner. *Product Image courtesy of Mirion Technologies (Canberra), Inc.*

It is the distribution of neutrons in time for specific isotopes of uranium and plutonium that allows the quantitative assay. While there are sources of single neutron events, fission events for nuclear material of interest produce ~2 or more neutrons on average per event.[36] These multiplicities are well-known and allow for the separation from single neutron events and are not related to fission. The number of neutrons emitted per second per gram along with the isotopic composition allows for the calculation of mass. While we will show just a few of these measurement systems, to better understand the counting system, a simple analogy can be made to a camera shutter as follows. Imagine a camera that can count neutrons and one that uses the first neutron to trigger the aperture of the camera to open for a short specified period of time. That period of time is based on the average lifetime of a neutron in the detector material. If no additional neutron is detected while the shutter was open, then the originating neutron that opened the aperture is considered a single neutron and, therefore, is not related to a fission event (referred to as an "accidental"). If additional neutrons are detected, these neutrons are considered to be coincident with the triggering neutron and therefore represent a fission event (referred to as a "real"). These "reals" are then summed over time and used to calculate mass.

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[36] Reilly D, Ensslin N, Smith Jr H, editors. *Passive nondestructive assay of nuclear materials*. Prepared for Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission; 1991.

In the case of plutonium, it is the even isotopes (^{238}Pu, ^{240}Pu, ^{242}Pu) that have the highest spontaneous fission rate (~5 orders of magnitude higher than ^{239}Pu). Therefore, to calculate the mass of ^{239}Pu requires knowledge of the isotopic composition of the plutonium, and this is the isotope of interest in terms of its use for reactor fuel and weaponization. The knowledge of the isotopic composition can be determined from an NDA technique such as gamma spectroscopy or a DA technique like mass spectroscopy. In the case of heat sources for radioisotope generators such as those used for space missions, ^{238}Pu is typically the isotope of choice and might be 80% or more of the total Pu. Within international safeguards, such material with a ^{238}Pu content that is equal to or greater than 80% is exempted from safeguards.

Fig. 7.12[37] shows a high-level neutron coincidence counter for passive neutron counting of plutonium in (a) and an active well neutron coincidence counter for neutron counting of uranium (b).

For uranium, all of the isotopes of uranium in the uranium fuel cycle have a low neutron emission rate. ^{235}U is the isotope of interest in terms of its use for reactor fuel and weaponization, and its neutron emission rate is ~2 orders of magnitude less than ^{239}Pu. As a fissionable isotope, ^{235}U can be fissioned by thermal neutrons, a source of single neutrons is placed in the end caps of the measurement well (AmLi is one example) and can be used to induce fission in this uranium isotope at a much higher and measurable rate. The same approach can be taken to measure uranium fuel assemblies by modifying the geometry of the detector to accommodate an assembly. As opposed to a well, fuel assemblies such as those for light water reactors are on the order of 2–3 m in length, so one side of the detector must have a movable door so the detector can be moved up to and around the assembly. The uranium neutron coincidence collar is used to calculate ^{235}U per unit length of an assembly and is shown in Fig. 7.13.[38] Recently, new fresh fuel has had thermal neutron absorbers (or burnable poisons) like boron added to flatten the neutron flux in the reactor allowing increased reactor power output. Since the uranium neutron coincidence counter measures thermal neutron, these neutron absorbers cause a negative bias. Solutions are being pursued to use fast neutron coincidence counters that are not impacted by these absorbers of thermal neutrons. This can then be combined with an active length measurement to determine total ^{235}U. One device that has an algorithm to measure active length is the HM-5.

Were nuclear material isotopes emit heat at a high-enough rate to be measured, another very accurate measurement approach that can be applied is a

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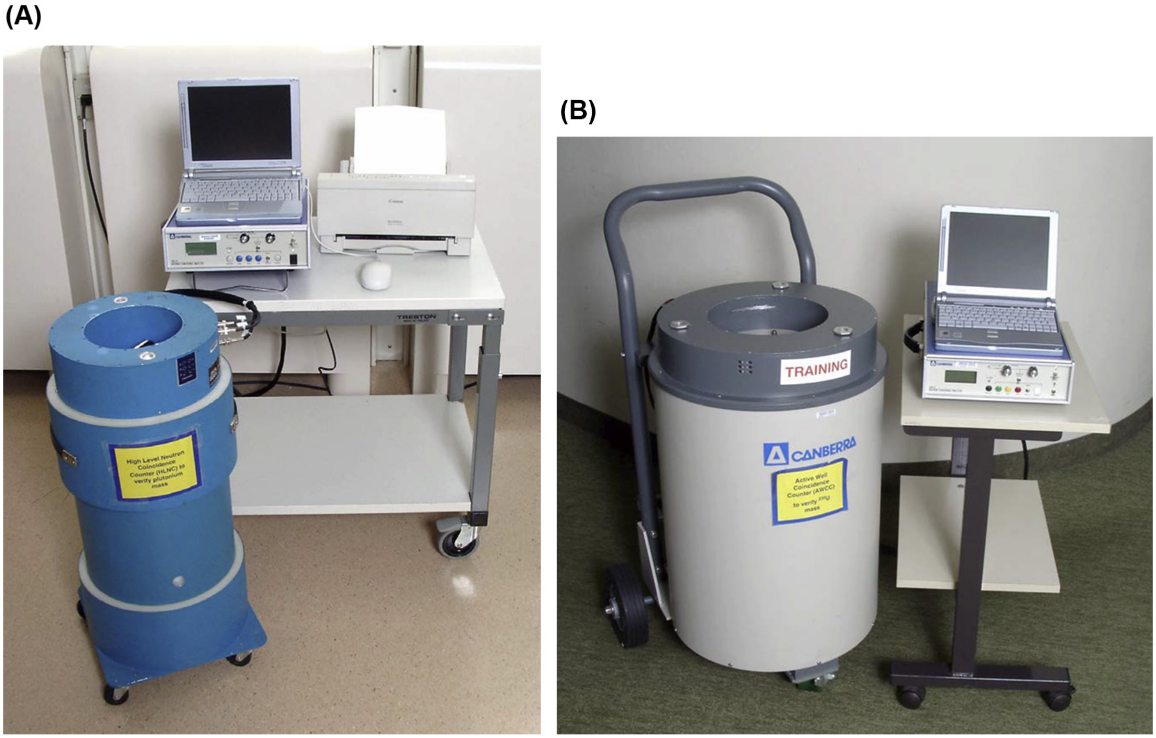
[37] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; pp. 21 & 24.

[38] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; pp. 25.



■ **FIGURE 7.12** (A) High-level neutron coincidence counter; (B) active well neutron coincidence counter.

■ **FIGURE 7.13** Uranium neutron coincidence collar. *Reproduced with permission from: International Atomic Energy Agency, Safeguards Techniques and Equipment, International Nuclear Verification Series No. 1 (Rev. 2), IAEA, Vienna (2012).*

■ **FIGURE 7.14** Antech Series 200 high sensitivity large sample calorimeter.

calorimeter. Plutonium is one example of an element with isotopes that have a high heat emission rate. In combination with known isotopes, the accuracy of mass measurements of plutonium using a calorimeter with good stability and control can match those of DA. Like quantitative neutron and gamma-ray measurements, a calorimeter measures the entire sample. Unlike neutron and gamma-ray techniques, a calorimetry assay is also independent of material matrix, geometry, and distribution. However, this technique is also slower than neutron and gamma-ray measurements and is typically on the order of hours versus minutes for neutron and gamma-ray techniques.[39] Fig. 7.14 shows a typical calorimeter design with the measurement well for an item on the left and the electronics on the right to control the temperature in the well. These units are designed to maintain a specific temperature in the well. Once a heat-emitting item such as plutonium is placed in the well and the well closed, the electrical power to maintain the set well temperature is reduced based on the additional heat emitted by the item. It is this change in the required watts to maintain the well temperature that can be accurately

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[39] Reilly D, Ensslin N, Smith Jr H, editors. *Passive nondestructive assay of nuclear materials*. Prepared for Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission; 1991.

determined once the system has reached equilibrium. The watts per gram of such isotopes like plutonium are well-known.[40,41]

So far, we have covered the NDA measurement of nuclear material that is not irradiated and therefore emits a low dose so personnel can safely approach and measure the items. This is not the case for irradiated materials, and here we are specifically discussing light water commercial power reactors or research reactor spent fuel assemblies. While there are very complex issues associated with measurements in a typical aqueous reprocessing facility using the plutonium uranium redox extraction (where spent fuel assemblies are chopped, dissolved in nitric acid, and then go through a separation process to separate fission products, transuranics,[42] and uranium and plutonium into oxides) or a pyroprocessing facility that separates the same or similar constituents in metal fuel using electrochemistry, we will focus on the spent fuel assemblies only from reactors that use water as a coolant.

There is no portable NDA system at this time that can quantify the plutonium in a spent fuel assembly. But there are a number of techniques that can confirm a fuel assembly or a fuel element is spent and not a substitute or a nonfuel item used in the core (in research reactors, absorber rods are used to flatten out the core flux and look identical to a fuel element).[43] While the availability of specialized hot cells can allow fuel assemblies to be safely measured in air, we will specifically look at a few techniques that are used at spent fuel storage ponds—see Fig. 7.15A[44]—where the spent fuel assemblies are stored in a water pool to safely cool them until the residual heat is reduced to a safe level (these assemblies could then be placed into dry storage casks for long-term storage or sent to a reprocessing facility to extract uranium and plutonium).

One technique that does not require insertion of an instrument into the storage pool is a Cherenkov viewing device. This is the characteristic blue light one can see either in a pool type reactor—see Fig. 7.15B—or in items recently removed from a reactor and stored in water. The emission of this light results from fission-product gamma rays that interact with the fuel cladding and water storage medium, producing electrons that in turn produce the Cherenkov light.

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[40] See footnote 39.

[41] Antech SERIES 200 High Sensitivity Large sample Calorimeter.

[42] An artificially made, radioactive element that has an atomic number higher than uranium in the periodic table of elements such as neptunium, plutonium, americium, and others. http://www.nrc.gov/reading-rm/basic-ref/glossary.html.

[43] Reilly D, Ensslin N, Smith Jr H, editors. *Passive nondestructive assay of nuclear materials*. Prepared for Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission; 1991.

[44] Image (a), IAEA image bank, image (b), advanced test reactor, Idaho National Laboratory.

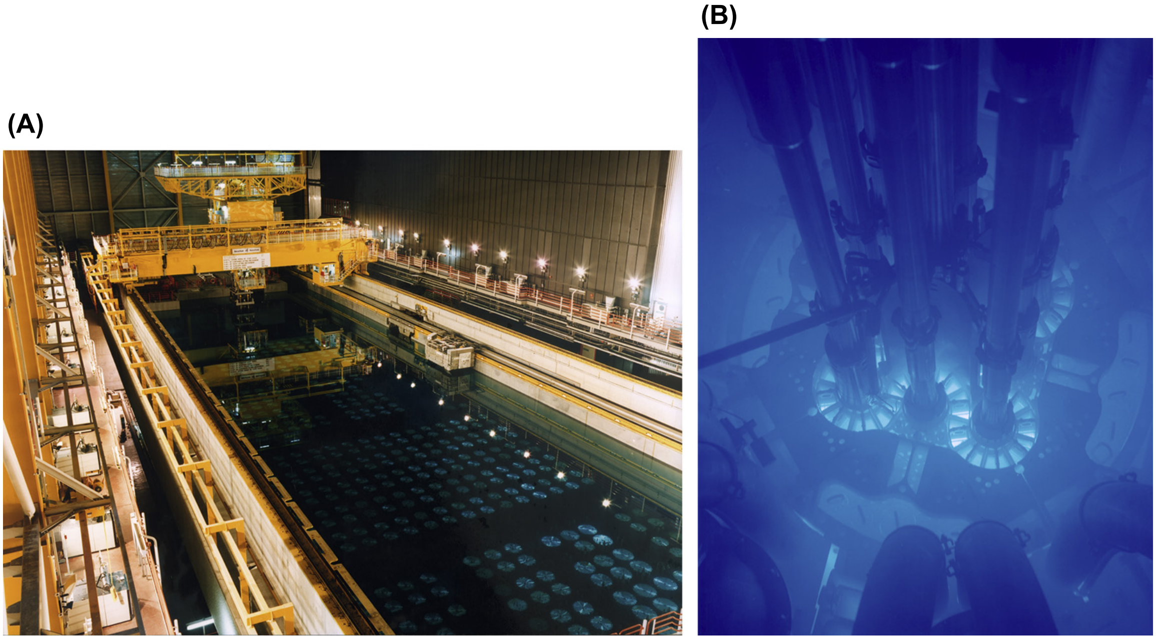

FIGURE 7.15 (A) Spent fuel storage pond; (B) Cherenkov glow.

The emission in the visible spectrum rapidly fades over time in a spent fuel pond, but the ultraviolet light in the 300- to 400-nm wavelength range can be measured using dedicated Cherenkov viewing devices. This does require an optically clear water medium and a smooth water surface (some ponds deploy bubblers as part of their purification system that disturbs the water surface, and this can distort the image). Fig. 7.16 shows two imaging systems, one called the Improved Cherenkov Viewing Device that does not record the image and the second called the Digital Cherenkov Viewing Device that does record the image, uses false color to indicate the most intense areas of light (see Fig. 7.17A), and can sum the intensity of the light to compare against the operator's declaration of spent fuel burnup (operational time in the reactor) and cooling time (residency time in the spent fuel pond). It also has the current sensitivity to determine if 1/3 of the fuel pins have been substituted for dummies (recent research has resulted in the development of a portable gamma emission tomography unit that can detect single pin defects).[45]

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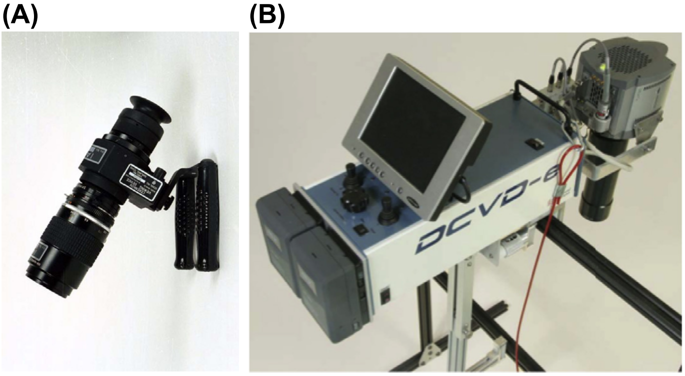
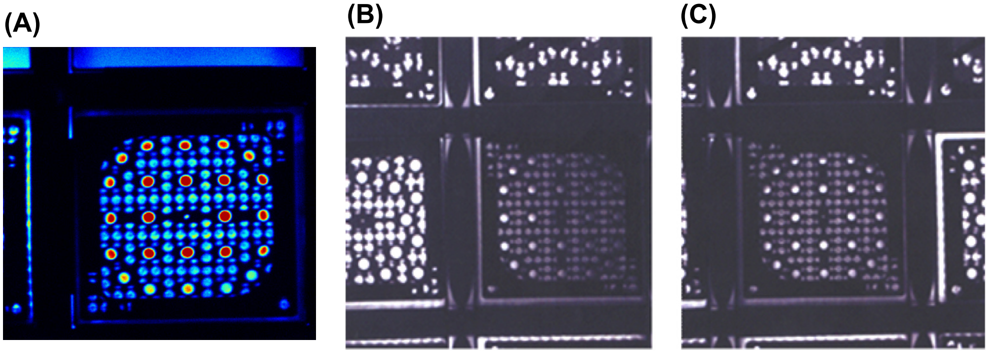
[45] Chen JD, et al. *Detection of partial defects using a digital cerenkov viewing device*, IAEA–CN–184/338.

The light that passes through the fuel assembly's cooling and control rod tubes that are not blocked will have a unique geometric pattern based on the reactor type (such as pressurized versus boiling water reactor). Besides the emission of the characteristic Cherenkov light from fission products, another characteristic is the collimation of that light since these assemblies are on the order of 3–4 m in length; see Fig. 7.17B and C.

We will finish this section by looking at two other radiation detection systems used on spent fuel to assess attributes to confirm that it is spent fuel. One is the irradiated fuel attribute tester (IRAT), and the other is the spent fuel Fork Detector (FDET). Both of these systems require immersion in the spent fuel pool, and the FDET requires the assembly to be moved to an



■ **FIGURE 7.16** (A) Improved Cherenkov Viewing Device (iCVD) and (B) Digital Cherenkov Viewing Device (DCVD). *(From* https://www.spectralcameras.com/.*)*



DCVD iCVD mis-aligned aligned

■ **FIGURE 7.17** (A) Digital Cherenkov Viewing Device (DCVD); (B) improved Cherenkov Viewing Device (iCVD) misaligned; and (C) aligned.

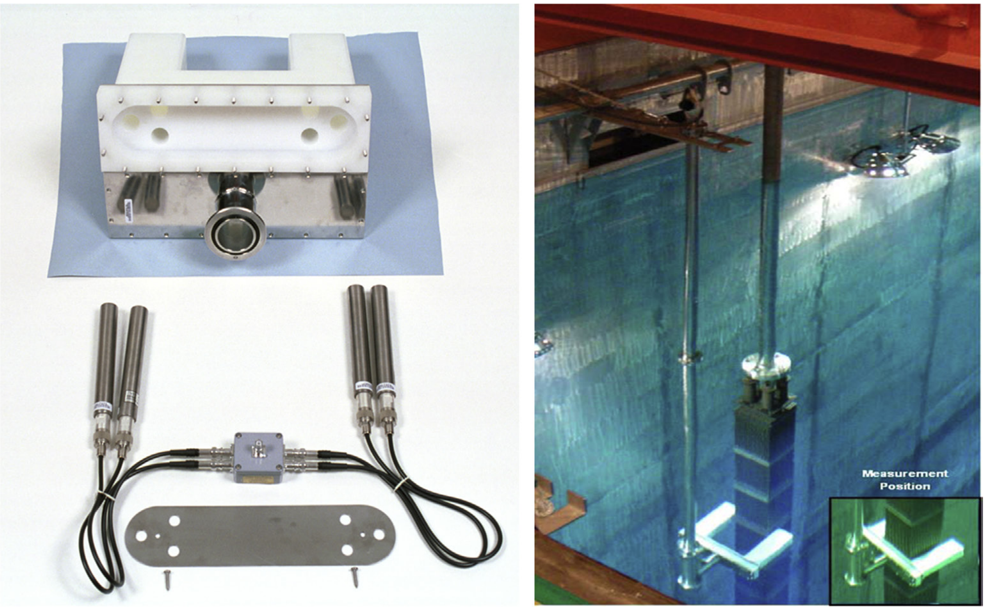


FIGURE 7.18 FDET detectors are used in the spent fuel pool.

area that allows space for this measurement. The need for that space will be apparent from the photo in Fig. 7.18.[46]

IRAT measures only gamma rays being emitted from the assembly and has spectroscopy capability (CdZnTe detector), so it can distinguish the peaks from any gamma rays above the continuum; see Fig. 7.19,[47] where the *y*-axis represents counts, and the *x*-axis represents energy. Note that unlike the gamma-ray spectrum for unirradiated material shown in Fig. 7.7, most peaks from isotopes are hidden by the gamma-ray continuum. Only cesium and cobalt are easily visible. The attribute indicating spent fuel comes from the fission product cesium as opposed to the higher-energy gamma rays from cobalt that indicate steel as in an absorber rod or structural material. SFAT measures both total gamma ray (ionization chamber) and neutron (fission chamber) emissions; these measurements and their ratio can be used to confirm the operator's declaration on the burnup and cooling time of the spent fuel assembly.

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[46] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; p. 28, and Presentation, Zendel M, Moeslinger M. *IAEA safeguards equipment*; 2007.

[47] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*; pp. 31.

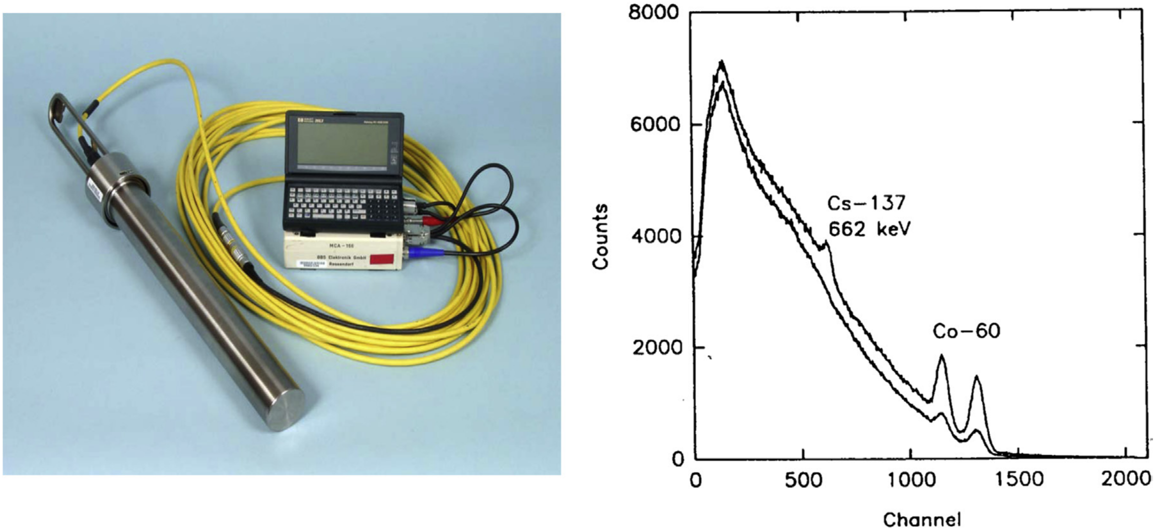

FIGURE 7.19 Irradiated fuel attribute tester (IRAT) and spectrum showing Cs and Co peaks.

We have now discussed a small sampling of both destructive and NDA systems. Measurement of nuclear material is a diverse field with many challenges throughout the NFC, and new techniques are constantly evolving.

That evolution can bring about new techniques or simply advances on existing techniques. The choices of specific measurement systems that a national regulator can make will depend on the requirements to draw safeguards conclusions within the regulations. Many of the techniques shown here are used by the IAEA and are commercially available.

Measurement Quality Control Program

A measurement quality control program is an essential part of an NMAC system to assure that all accountable nuclear material (NM) is at a measured value at the uncertainty level required by the regulatory authority (e.g., international target values)[48] and is defensible[49] on each item in the inventory and on all items shipped or received. Besides supporting the regulatory and criticality requirements, accurate measurements also help deter and detect unauthorized removal as well as identifying potential process upsets

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[48] International target values 2010 for measurement uncertainties in safeguarding nuclear materials, STR-368, IAEA, Vienna, November 2010.

[49] Note: By defensible, we mean that documentation is available to prove that the correct technique was used on the nuclear material item, that the technique was properly calibrated, that the item measured was in the calibration range, and that the instrument was in statistical control at the time the item was measured.

where expected throughput for a process is not functioning correctly, all in a timely manner. To assure that measurement systems fulfill these requirements in a reliable and sustainable manner, a number of important practices must be deployed.

The measurement technique selected for the NM must be one that is appropriate for the material and the required measurement uncertainty. To assure that this is the case, all measurement techniques used for accountability purposes should be authorized prior to their use through a certification process.[50] Elements of a strong certification process include:

1. proof of principle of operation for application to the NM in question;
2. manufacturer's stated accuracy and precision;
3. NM chemical form(s) to be measured;
4. NM mass range to be covered;
5. item geometry limits;
6. range of assay times;
7. calibration method;
8. calibration standards covering the mass range;
9. Measurement Control Program (MCP);
10. failure response plan when a measurement control standards fails;
11. Data Collection and Assessment Plan (DCAP) designed by the statistics group and initiated in the instrument's operational location after calibration. This plan will establish the instrument's stability and measurement control limits over the range of operations, and will be compared to a superior technique, if possible;
12. comparison to other techniques used on the same items;
13. reference the operator's training program;
14. certification approval documentation;
15. postcertification extension to new material classes, as required; and
16. requirements if the instrument is moved or modified.
17. use of an instrument logbook to record all activities associated with the operation, maintenance, and repair.

All of these elements play a role in assuring the best outcome in certifying an instrument. The authors have experienced the results of not implementing certification using this approach. One case concerned the certification of a mass spectrometer to be used for the measurement of tritium. The users, without consultation with the statistician, had already implemented

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[50] Procedure to Certify Instruments/Techniques for Nuclear Material Accountability Measurements, LA-UR-99-1756, W. Sedlacek, et al, editors. *The sixth international conference on facility operations-safeguards interface*; September 20–24, 1999.

their own DCAP and expected immediate certification, as they were under pressure to utilize this capability. The accountability group and the statistician noted that instead of a random DCAP, the user conducted all measurements from the lowest to the highest standards in all of their measurements. When this was pointed out, the user assured us that it would make no difference, as proper procedures were followed. Nevertheless, the certifying accountability group insisted that a few more measurements be conducted based on the statistician's random plan. The user reluctantly agreed and indicated that they would be right back with passing results. After hearing nothing for 3 weeks, contact with the user revealed that they had failed to properly clear out the sample chamber from previous assays, and this resulted in erroneously high measurements of low standards when they followed a high standard.[51] It was a good lesson about why good practices should always be followed.

Another consideration when certifying a new instrument that will replace another older instrument is to fully understand any biases between techniques. This is easily accomplished if there are items in the inventory measured on the older technique. Certification should then require the remeasurement of these items using the new technique along with an analysis to determine if there is any bias between techniques. This approach assures the statistical variation between techniques is fully understood and defensible so that differences in inventory items using the new technique can be shown to be the results of bias and not loss or gain of nuclear material.

It should also be pointed out that a manufacturer's stated measurement uncertainty for an instrument/technique is not necessarily the measurement uncertainty a user will obtain under actual operating conditions. A manufacturer will perform uncertainty tests under ideal (typically laboratory) conditions, whereas an operational environment can change the performance of an instrument due to many factors; some of which include: unstable power, multiple operators, nearby instruments, nearby measurement items, nearby facility operations that radiate noise, etc.

1. Certified reference materials (CRM)
To know if an instrument is giving an accurate result within it uncertainty bounds, a known standard is required to test and calibrate the instrument. International guidelines are available that assist in the selection, use, and

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[51] Recollection of M. Schanfein on certifying a tritium mass spectrometer at Los Alamos National Laboratory.

common definitions for such materials[52,53,54]. A number of international sources for certified reference materials (CRMs) are available[55,56,57]. CRMs are the highest level of standard commercially available. However, they are expensive and are not available for all NM of interest. Often a reference material (RM) might be purchased instead that is traceable to a CRM if it provides the necessary measurement uncertainty needed for an instrument or technique. CRMs and RMs typically have measurement uncertainties that are two to three orders of magnitude less than the technique they are calibrating.

NFC facilities have a diverse range of nuclear materials in many different forms. Many of these forms represent a significant challenge to measure accurately. This is particularly true for process residues and waste forms. These tend to be heterogeneous and often have other nonnuclear material contained. This may include low density components such as plastics or high density such as metals. There are no CRMs or RMs for materials like these. The measurement of nuclear materials contained in these challenging cases still has to be done in a defensible manner. One possible solution is to develop working standards where a facility makes their own standards at a lower quality level than either CRM or RM, but still traceable. This is where subject matter experts in both DA and NDA techniques play an important role. It is not unusual for facilities with research and development capability to develop either their own traceable standards or to conduct special tests to prove their measurement capability. One example of a special test might be the measurement of four waste drums of low-level, low-density waste. Consider a pair of waste drums at a low range and a pair of waste drums at a high range that have matching responses in the measurement system. To develop a working standard, the facility carefully incinerates the contents of one low- and one high-range drum and then homogenizes each containers contents. With the nonnuclear material significantly reduced, DA samples are taken as well as mass measurements. Based on the DA and weighing (both traceable to a CRM/RM), the nuclear material in each processed drum is now known, and the matching drums are now authorized as a "working standard" to calibrate the measurement system. However, the cost associated

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[52] Development and use of reference materials and quality control materials, 2003, IAEA-TECDOC-1350.

[53] *Guidelines for the selection and use of reference materials*, ILAC-G9:2005.

[54] Reference materials - Good practice in using reference materials, ISO Guide 33:2015.

[55] http://www.nist.gov/pml/div682/grp04/radioactivity_srm.cfm.

[56] https://ec.europa.eu/jrc/en/reference-materials.

[57] http://science.energy.gov/nbl/certified-reference-materials/.

with trying to make standards for each matrix could be prohibitive. In addition, the variation in some matrices, especially waste, can be so variable that each one is unique. We will discuss approaches to resolve this dilemma in the following sections. It should also be noted that the generation of working standards adds one more level of measurement uncertainty which must be considered when determining the overall uncertainty of the measurement of an unknown.

2. Calibrated measurement systems
   Once an instrument or technique has been installed and is ready for calibration, CRMs or RMs are used to calibrate the systems. Good practice dictates that these standards bound the upper and lower ranges of masses for which the system is authorized to measure. A calibration fit is then made to these two or more standards to calibrate the system. The nature of the fit depends on the technique and can vary from straight lines to various curves. It is also typical that such fitting is not perfect for all calibration standards, resulting in some bias associated with the calibration. Calibration frequency is another question that is often answered by the regulations. It is not unusual to see requirements for NDA instruments to be calibrated at least once per year or monthly, depending on the type of system. NDA systems tend to be highly automated, eliminating many variables that might impact measurement, such as those introduced by the operator of the technique. DA measurements are highly dependent on the operator and the procedures followed during both sample preparation and measurement; therefore, calibrations are often made for each measurement campaign. However, many DA activities are becoming more and more automated to reduce unintended errors and other variables.
3. Measures standards to monitor systems
   Once a measurement system is calibrated, how do you assure it is still in statistical control so that every measurement made on the instrument is defensible? The answer is to have a valid measurement control program (MCP).[58] We define a defensible measurement as one that can be demonstrated to be from an instrument or technique operating within their desired levels of bias and precision[59] (the lack of uniform terminology to describe error can be quite confusing). In this case, we define bias or systematic error as a fixed error, either positive or negative, that remains constant over the entire measurement range of an instrument

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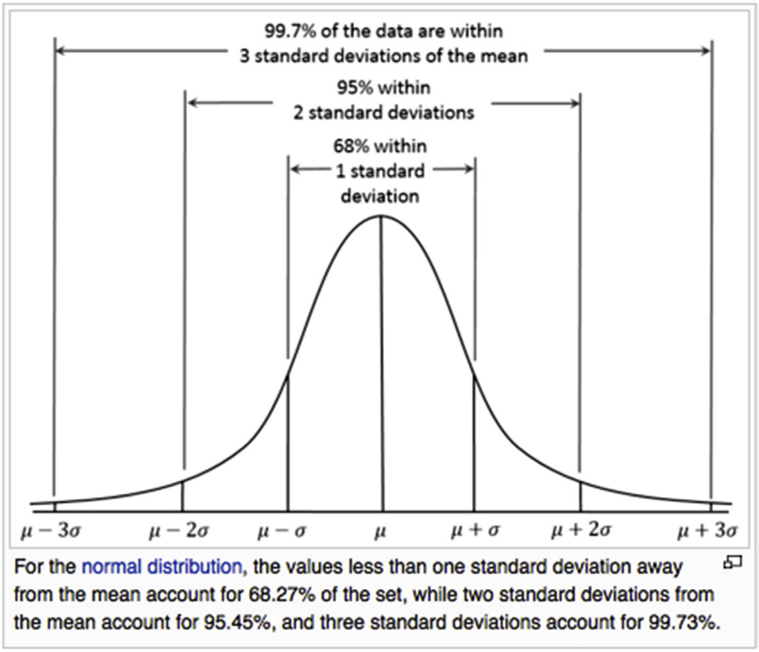
[58] Schanfein M, Bruckner L. *A practical guide to measurement control experience on non-destructive assay equipment at the Los Alamos National Laboratory Plutonium Facility*, LA-UR-99-2963; 1999.

[59] Bruckner LA. A measurement control program to meet desired levels of precision and accuracy. *Journal of Nuclear Materials Management* 1990;**XVIII**:29–33.

(for example, an electronic balance at home might always measure anyone using this balance as 2 kg above their actual weight). Precision or random error is an error that fluctuates around an average value for each measurement of an item (for example, an electronic balance at home might always measure anyone using this balance as somewhere between the range of −0.5 to +0.5 kg of their actual weight 95% of the time).

To demonstrate that an instrument or technique is operating within the desired level of bias and precision, measurement control standards are measured and the responses evaluated. This standard could be the same standards used for calibration or similar ones. The certification process for the instrument or technique now defines how the MCP is implemented for each system. Based on the results from the DCAP, the standard deviation (σ) is calculated and used to define both warning (±2σ) and action (±3σ) limits. Fig. 7.20 shows how the standard deviation represents an expected population of measurement results in a normal distribution.



For the normal distribution, the values less than one standard deviation away from the mean account for 68.27% of the set, while two standard deviations from the mean account for 95.45%, and three standard deviations account for 99.73%.

■ **FIGURE 7.20** Normal distribution where μ = true value.[60] *(Source: By Melikamp [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons.)*

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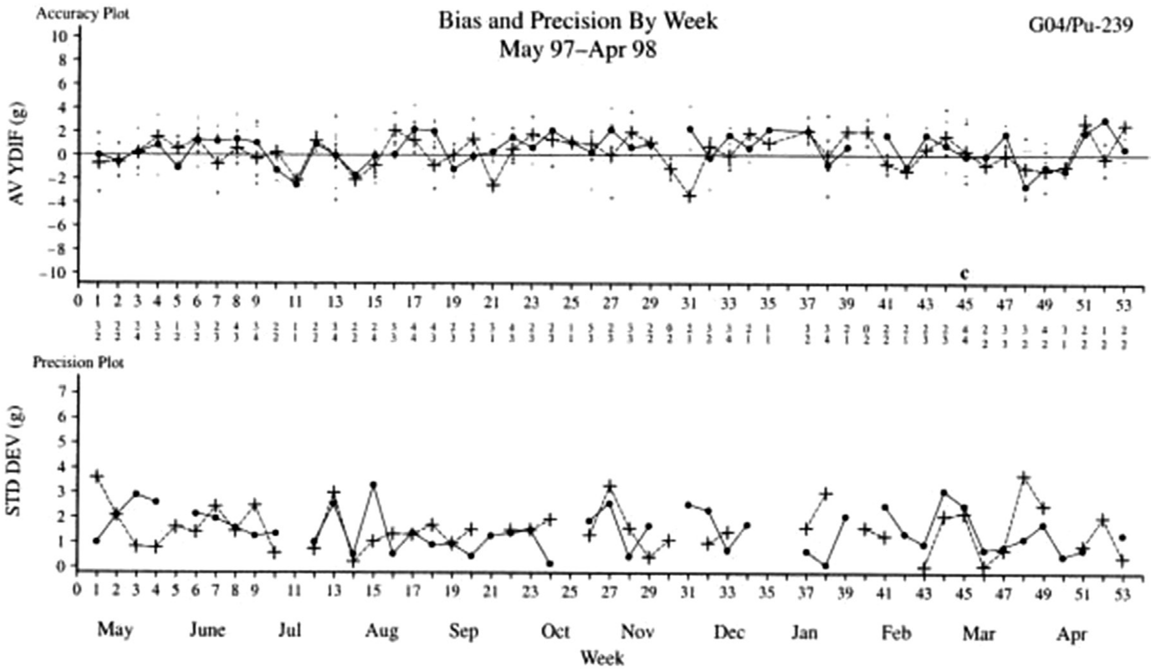
[60] https://en.wikipedia.org/wiki/68–95–99.7_rule.

Keep in mind that limits on a new instrument are based on an initially small dataset, and they need to be reevaluated as more historical data is collected over time. The use of such immediate tests is often defined as a requirement in regulatory documents. These limits are then used to establish procedures to be followed by the operator. These procedures might define the following actions. If the measurement control results fall within the ±2σ limit, the instrument is considered to be in control and ready for accountability measurements. In the case of a warning limit failure (measurement result is greater than ±2σ but less than ±3σ), the standard must be measured again, and if it passes the system, it is considered to be in control. For any action limit failure (measurement is greater than ±3σ), the system is considered to be out of control, and it is placed out of service for investigation by the appropriate staff. Such actions to take should be detailed in a failure response plan. Note that with these immediate warning and action limits, there is still a possibility of indicating a problem, even when the instrument is performing normally. False positives, while of low probability, are still possible. These false positives must be addressed efficiently to avoid unnecessary measurement stoppages. This again should be captured in the failure response plan. It should be pointed out that there are many statistical tests that can be used to determine if a system is in statistical control. Employing more tests is not necessarily better, since each test has a probability of indicating a problem when an instrument is performing normally. The more tests, the higher the probability of these false positives.

Prior to the start of accountability measurements on any system, a measurement control standard is measured. Assuming it passes the measurement control test, accountability measurements are made. On some frequency, a repeat measurement control test is made again. If this passes, then the set of accountability measurements bounded by the two passing measurement control tests now represent defensible measurements. This also means that proper records of all of these activities must be kept and available to prove the case for defensibility. While hand calculations and written records can and should be made (an important record should any electronic database be lost or compromised), it is more typical for all of these activities to be captured in a computer MCP database. What if the second measurement control test fails? In this case, all of the measurements after the prior passing measurement control test are now suspect and need to be remeasured once the instrument is back in statistical control. The procedure to recover from such a failure will define the necessary steps. For example, the procedure might require remeasurement in the reverse order that they were measured. If it was found that three items in a row matched their initial values (within statistical limits), we considered this the point in which the instrument went out of statistical control and stopped the remeasurement. All prior measurements are now validated as good measurements.

How often should measurement control tests be done? This will be based on three factors including the nature of the instrument, its working environment, and the consequences of failure. Consider an instrument that takes minutes to complete a single assay versus one that takes hours. For example, neutron coincidence counting might take 30 min to complete an assay, so measurement control standards will be measured at the beginning and the end of the day, whereas calorimetry measurements might take from 4 to 8 h to complete an assay, so a measurement control standard will be measured once per week. A very stable instrument would require fewer measurement control tests than one that shows high variability. On the other hand, even a stable instrument could show high variability in a working environment and so the need to characterize it in this environment. Finally, no matter how stable the instrument, evaluating the ability to recover from a measurement control test failure can define the frequency. For example, if, after an accountability measurement is completed, the item goes into a process and is irrevocably changed or has been shipped from the facility, the ability to recover from a future measurement control failure on that item is no longer possible. Worse, if the item is now in a different form, it might no longer be measurable, so the measurement error might propagate into new inventory locations, making recovering far more complicated and costly. Under such circumstances, and even with a very low probability of a measurement control failure, the measurement control test frequency will be done such that recovery is possible on the item before it enters the process or is shipped out of the facility.

4. Statistical quality control charts
The measurement control tests described in the previous section are one-time immediate tests. But what if you could predict and thereby prevent a measurement control failure? How do you develop more accurate measurement control limits over time? This is where trend analysis through analysis of historical data plays an important role. Looking at a system’s performance over an extended period of time provides more reliable and representative data for both setting limits and detecting trends that might indicate future problems. Using a control chart allows one to plot all measurement control data and periodically analyze the data. This same data can be used to prove the overall performance of the instruments under measurement control. Quality control charts are developed per instrument.



Standard	Symbol	Number Weeks	N	Mean (% RDIF)	Std Dev of % RDIF Daily Data	Std Dev of % RDIF Pooled Weekly
9.625	Solid	50	126	0.545	1.773	1.643
96.268	Dashed	52	126	0.322	1.827	1.804

Scaling	Min	Max
Bias	−10	10
Precision	0	7.5

0 Value(s) omitted

■ **FIGURE 7.21** Control chart for instrument G04.[62]

Fig. 7.21 shows the 12-month control chart for a gamma counter with a unique instrument code: G04. Low and high standards of 9.6 g (solid line) and 96.3 g (dashed line) of ^{239}Pu were used to perform measurement control tests.[61] The upper plot shows an estimate of the bias or systematic error for each standard. Note: it is the average difference per week (individual points for each week are plotted along with the average). The lower plot shows an estimate of the precision or random error. Details for all of the data in this plot can be found in reference[58]. Just viewing this chart over the 1-year period shows

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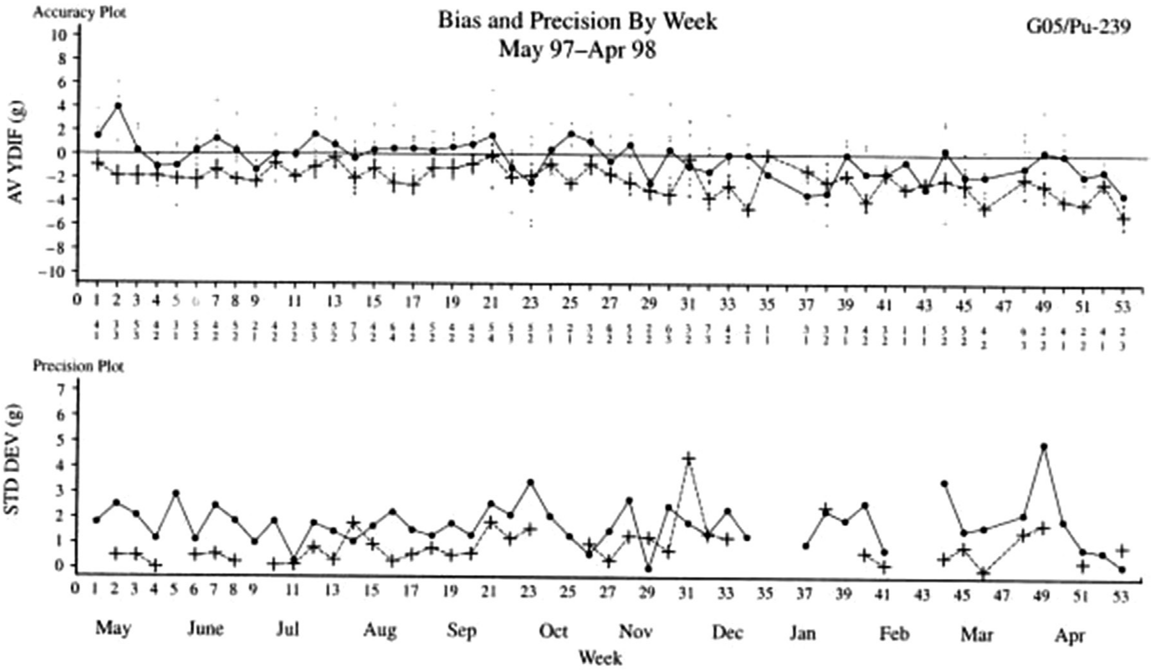
[61] Schanfein M, Bruckner L. *A practical guide to measurement control experience on non-destructive assay equipment at the Los Alamos National Laboratory Plutonium Facility*, LA-UR-99-2963; 1999.

[62] Schanfein M, Bruckner L. *A practical guide to measurement control experience on non-destructive assay equipment at the Los Alamos National Laboratory Plutonium Facility*, LA-UR-99-2963; 1999.

a stable instrument. The uncertainty associated with these standards can be applied to inventory items that are appropriately represented by these measurement control standards. Now let's look at Fig. 7.22. Without any analysis of the data and just using your eyes, it is clear that something has changed in the instrument's performance starting around week 30. We can see a negative shift in the bias and an increase in the precision at the same time. This is the simple power of a plot that can allow us to see a trend in an instrument's performance before there are any daily measurement control standard failures. Based on this information, those responsible for maintaining these instruments can intervene early to correct this trend before it impacts the items being measured.



Standard	Symbol	Number Weeks	N	Mean (% RDIF)	Std Dev of % RDIF Daily Data	Pooled Weekly
9.625	Solid	51	198	−0.148	2.21	2.044
96.268	Dashed	51	102	−2.052	1.458	1.231

	Scaling Min	Max
Bias	−10	10
Precision	0	7.5

0 Value(s) omitted

■ **FIGURE 7.22** Control chart for instrument G05.[63]

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[63] Schanfein M, Bruckner L. *A practical guide to measurement control experience on non-destructive assay equipment at the Los Alamos National Laboratory Plutonium Facility*, LA-UR-99-2963; 1999.

With this ability to preemptively act to correct instrument issues before they impact accountability measurements, this timely ability to correct prior to failure can also be used to address the issue of calibration frequency. If one can show that the occurrence of all warning and action limits are within their expected probability and the trend analysis catches changes on instrument performance before they can impact the quality of the accountability measurements, then one has a strong technical argument that calibration frequency should be driven by the MCP and not at a fixed frequency. However, as mentioned in the calibration section, frequencies may be specified as a compliance requirement in regulatory documents. This is one area where one can see the potential positive impact of a performance-based requirement as opposed to a compliance-based requirement to improve the efficiency of the MCP.

5. Replicate measurements

These measurements are a repeat of measurements on the same item for the purpose of accurately calculating random error. This does not mean that, for example, the button is pressed to repeat measurements on an item again one right after the other. While that might capture some random error, it is not a good practice since the full procedure for measurement is not repeated, such as placing the item in a measurement chamber or preparing the item for the measurement system. In addition, day-to-day, month-to-month, and year-to-year variations are not captured. For example, month-to-month measurement control data for calorimeter has shown a baseline drift that is associated with the changing humidity in the local environment over the year.

What is important about these measurements is that they are not dependent on a standard and capture the natural variation in the measurement process over time. Such a measurement program is sometimes called a “remeasurement program” and is formalized as part of the MCP and applied both to all measurement techniques employed and the various material types and matrices in the inventory.

What is far more challenging without a matching CRM, RM, or working standard is to understand the bias or systematic error. It might be possible to do this by using a more accurate technique to compare with the result of a less accurate technique. This is possible, for example, when measuring plutonium, where calorimetry can be used on items that have been measured by gamma and neutron systems. This can also be captured in a remeasurement program.

Another good practice in the area of DA is to participate in an interlaboratory comparison program. Subsamples of the same NM are sent to participating laboratories for analysis. This intercomparison is then reported to all of the participants. By comparing results, opportunities for improved performance might be identified. In addition, should the participating laboratories ship and receive NM between their facilities, any differences in measurement results on the same items revealed through shipper–receiver difference (SRD) analysis might be explained by biases revealed from the comparison program.

6. Estimates of measurement uncertainty
All of the previous sections have discussed all of the actions management should take to establish a robust and reliable MCP so all NM at an accountable value can be defended. This also results in the ability to defend the uncertainties associated with each item based on the measurement system(s) used to establish that accountability value that is listed in the book inventory.

Knowledge of the measurement uncertainty for all nuclear material plays a key role in many required activities at a nuclear facility. Some of these activities are listed below:

a. Ability to analyze the MUF at the end of a material balance period following a physical inventory taken to determine if any difference is statistically significant. When the measurement uncertainty is propagated for all items to determine the MUF, the propagated uncertainty is also used to determine if the difference between the book and physical inventories are within the expected measurement uncertainty bounds.

b. Ability to reverify the NM accountability value during national and international inspections. In bulk facilities due to measurement uncertainty, reassaying an NM item will typically result in a difference between the book and new measured value of an item. However, if the result falls within expected uncertainty, then the difference is not of statistical significance for that item. See Fig. 7.4.

c. Ability to accurately assess Shipper Receiver Difference (SRD) to assure that all of the material shipped or received is present.

d. Ability to detect unauthorized removal of nuclear material anywhere in the facility.

e. Ability to provide accurate NM quantities for criticality control.

Shipper–Receiver Evaluation

Shipments from a facility and receipts to a facility must be evaluated to assure that all of the NM contained is as declared. The transportation of NM opens up the possibility for both malicious acts as well as unintentional errors. The entire process of preparing NM for shipment or receipts requires communications and agreements between the two parties. This covers not only the commercial considerations to meet the purchaser's requirements but the regulatory requirements of the NMAC system. As a part of these requirements, both parties agree on a shipper–receiver agreement. Such an agreement typically details:

- responsibilities of both parties
- preparations and notifications
- records to be provided
- nature of the NM to be delivered
- TIDs applied
- measurements to be taken by both parties. The agreement may also include the steps to be taken should the shipper's measured values and the receiver's measured values exceed the combined limits of error. This may include acceptance by one party of the other's values or possibly sending a representative sample to neutral laboratory for arbitration.

Physical Inventory

The purpose of the physical inventory is to determine the quantity of nuclear materials on hand at the time of the inventory, to compare it to the book inventory,[64] and to investigate and resolve significant differences between the physical inventory and the book inventory.[65] Proper performance of physical inventory taking (PIT) is essential not only for ensuring that the accounting records accurately reflect what is physically in the MBA but also for assuring that nuclear material is not missing due to possible theft or diversion.

Introduction

For each MBA, accounting records should be updated when nuclear material is received, placed in the process, removed from the process, and shipped from the MBA. Thus, the accounting records should be able to produce a "book" inventory of the amount of material present in the MBA at any given time. Periodically, physical inventories are taken to determine the accuracy of this book inventory. Once complete, and all discrepancies between the physical inventory and book inventory are resolved, the book inventory is adjusted to establish agreement between the book inventory and the physical inventory.[66] The adjusted inventory then serves as the starting book inventory for the next inventory period, and the cycle continues. The frequency of the PIT will depend on the quantities and attractiveness of the nuclear

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[64] DOE O 742, Chang two.

[65] Department of Energy Standard DOE-STD-1194-2011, Change Notice 3. *DOE standard – nuclear materials control and accountability*, DOE; 2013.

[66] IAEA NSS No. 25-G.

material in the MBA.[67] Similarly, the function of the MBA will dictate how the physical inventory is taken and how discrepancies in the physical inventory and book inventory are resolved.

Frequency of the Physical Inventory Taking

Each MBA is categorized on a graded approach, established either by state regulations or international (IAEA) recommendation, based on the quantity and attractiveness level[68] of the nuclear material present in the MBA. The larger the quantity and more attractive the material is in the MBA, the greater consequence of a malicious act, thus, the more frequent that a physical inventory should be performed to ensure no material is missing. The state competent authority establishes the frequency in which physical inventories should be taken for each category of MBA.

For example, Category I MBAs may be inventoried every month, while Category III may be inventoried every 6 months.

There are other considerations that may also be used to define the frequency of inventory taking, including function of the MBA (e.g., processing versus storage), additional security measures present in the MBA, and the use of process monitoring. For facilities that have multiple MBAs of varying category levels, and thus inventory frequencies, the state competent authority may also require a frequency in which all MBAs are inventoried at the same time.

Physical Inventory–Taking Process

The methods of taking a physical inventory will vary depending on the material to be inventoried and the type of operations conducted at the facility. In general, all nuclear material should be measured using an approved measurement system at the time of PIT or should have a prior measurement whose integrity is assured by a TID. (Fig. 7.22)[69] Items that are tamper indicating or have been sealed with a TID and have been continually under an effective material surveillance program do not need inventory measurements. If there is no indication that an item has been altered, the previous measured value may be used in calculating the material balance.[70]

For all inventories, a cutoff date and time is established to separate the transactions from one inventory period to the next. Typically, all movement of

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[67] See footnote 66.

[68] DOE Order 474.2.

[69] IAEA NSS 25G.

[70] Department of Energy. *Inspector's guide – Nuclear material control and accountability*, DOE; October 2009.

■ **FIGURE 7.23** Conducting a physical inventory. *Reproduced with permission from Safeguards Implementation Practices Guide on Facilitating IAEA Verification Activities, IAEA Service Series No. 30.*

material across MBA boundaries is suspended until the PIT is complete. The exception to this would be inventory samples leaving a processing MBA for destructive analysis.[71]

Item Material Balance Areas

MBAs where no processing or change to the nuclear material is performed and the nuclear material is in the form of discrete items, such as containerized material, fuel rods, metal components, etc., are considered item MBAs. These are typically the simplest type of MBAs to perform and reconcile against the book inventory (Fig. 7.23). For such MBAs, where the material is protected under a TID or is intrinsically tamper indicating, a physical inventory usually consists of checking the unique identification of each nuclear material item by visual observation, the identity and integrity of its TID (if one has been applied to the item), and its location. There should be no MUF, as this would represent a missing item.

The most efficient method for performing an item inventory is to utilize barcode technology. This requires not only the electronic components of a handheld barcode scanner and barcode printer but also software that can interface with the electronic accounting records to generate discrepancies. Depending on the facility, item barcodes may be applied directly to the item

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[71] *Safeguards implementation practices guide on facilitating IAEA verification activities, service series 30*; p. 21.

or container or a "batch card" that accompanies the item. If the latter is used, material control elements must assure that the item and card cannot be separated by an insider trying to divert material. Barcodes can also be applied to the storage locations within the MBA as well as imprinted on the TID used to protect the item. By scanning the item, TID, and location barcodes for each item in the MBA, a rapid physical inventory is obtained and can be readily compared to the book inventory. Any missing or additional items would be investigated.

The use of barcode technology provides many advantages over handwritten verification of inventory. First, it eliminates any transposition errors associated with conducting the inventory. Second, it can greatly reduce the amount of time necessary for taking a physical inventory of MBAs. This is especially valuable for MBAs with large numbers of items or MBAs with items that pose a radiation health risk and where time spent in the area should be minimized. Use of barcode scanning also minimizes the ability for an insider to falsify the inventory in an attempt to hide a theft or diversion of material.

Use of barcodes can also have a disadvantage in creating an environment where other aspects of the physical inventory are not performed as required. As mentioned, the PIT should not only include verification of the item identification and TID identification but also the integrity of both. Without an effective nuclear security culture, personnel may become complacent with checking the integrity of the TIDs. Also, due to some operating environments that a container or item may see when processed, such as UF6 cylinder in an autoclave, a barcode might not survive the process. In these cases, a hand inventory is completed.

When barcode technology is not used, the physical inventory procedure may use either a prelist of the book inventory generated by the accountability computer to locate items or a hand list of items may be generated during the inventory, and the list is compared to the accountability records.[72] The advantage of the former is that it can provide immediate notification when an item is missing and also minimizes the transposition errors associated with generating the hand list of items during inventory. The disadvantage is there is a greater likelihood of not inventorying items that are present but not on the book listing (e.g., once all items on the book listing are located, the personnel taking the inventory stop the process).

Regardless of the method of hand inventory that is conducted for MBAs with large numbers of items or where potential radiation exposure to personnel

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[72] DOE Standard DOE-STD-1194-2011.

is an issue, 100% item inventory may not be desirable or possible. In lieu of a 100% item inventory, the site/facility operator may define a statistical sampling plan. Such statistical sampling would include random selection of a defined subset of the entire inventory and would be based on a graded approach. One such method for determining sample size is:

$$n = N(1 - \beta 1/d)$$[73]

Where N is the population size, d is a conjectured or assumed number of defects (altered or missing items that cannot be reconciled or located), and β is a tolerable probability that none of the defects will appear in a random sample of size n if there are in fact d defects within the population. In other words, β represents an acceptable probability of not sampling any of the d defects and therefore erroneously concluding that the population contains less than d defects, when the actual number of defects is equal to d. The equation provides a suitable estimate of the required sample size, provided that the sample is large (at least 30) and is a small proportion of the population (less than 10%) and that the number of defects is also a small proportion of the total population (less than 10%). In addition to calculating the required sample size, randomly selecting those items for measurement/check removes any selection bias further strengthening the inspection process. Often a random number generator is used for this purpose.

If a defect is found, then additional verifications are warranted up to and including 100% inventory of the population.

Item Measurements During Physical Inventory Taking

In addition to item and TID identification and integrity checks, the State competent authority may also request confirmation measurements of some or all of the items. Confirmation measurements are a qualitative or quantitative measurement made to verify the integrity of an item by testing whether some attribute or characteristic of the nuclear material in the item is consistent with the expected attribute or characteristic of the material. The measurement method used for confirmatory measurements must be capable of determining the presence of a specific attribute of the material, consistent with valid acceptance and rejection criteria.[74] Such attributes may be an enrichment signal or value or weight of the item.

For items not intrinsically tamper indicating or not protected under TID, verification or accountability measurements are performed on the items. Verification measurements are a quantitative remeasurement of the amount

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[73] See footnote 72.

[74] See footnote 73.

of nuclear material in an item made to verify the quantity of nuclear material present.[75] Verification measurements may include NDA measurements for the total U or Pu content in an item or container. Verification measurements, when used to adjust accountability records, must have accuracy and precision comparable to or better than the original measurement method.[76] Accountability measurements are a defensible quantitative measurement of the amount of nuclear material in an item or location made to establish initial book values for the material or to replace the existing book value with a more accurate measured value. Such measurements are discussed in earlier sections of this chapter.

Processing or Bulk Material Balance Areas

Unlike item MBAs, processing or bulk MBAs provide a much different challenge when conducting a physical inventory. For processing MBAs, the nuclear material will go through some form of change either physically (e.g., batching in to smaller or larger containers, pressing of oxide powders into pellets, etc.) or chemically (e.g., conversion from yellowcake to UF_6, oxides to metal, etc.). When this occurs, the resulting product, by-products, and/or waste are measured. As with any such process, due to measurement uncertainties, the difference between the measured inputs to the process and the measured outputs will not equal zero. Thus, it is expected that the processing MBA will have MUF. However, the purpose of the physical inventory is to ensure that any MUF falls within expected measurement uncertainty.

Some materials in a processing MBA will be intrinsically tamper indicating or under TID similar to that of an item MBA, and therefore inventoried using the same methodology as an item MBA (this assumes that the accounting values were determined prior to being placed under TID). However, not all nuclear material in the MBA will be containerized or in discrete item form at the start of the inventory process. Depending on the process, a significant quantity of nuclear material may be in the process equipment and must be inventoried in order to close the material balance.

Ideally, the facility would suspend production, remove all material in process, and measure the material removed as part of the ending inventory. However, in reality, this is rarely achievable, and the facility must determine how the PIT can best be accomplished. Several factors go into this decision, including the time and cost it takes to perform the inventory, cost associated with loss of production while the inventory is being taken, and how accurate the facility can measure or estimate the amount of material still in

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[75] See footnote 74.
[76] See footnote 75.

the processing equipment. Failure to get an accurate value for the amount of inventory still in the process may generate MUFs that exceed allowable limits. This would require the facility to keep operations suspended and/or reinventory the MBA until the cause of the MUF could be determined.

Some operations are not conducive to having the material removed from the process without risk to personnel and/or major disruptions to the process. For example, removing all gaseous uranium hexafluoride from an enrichment cascade would not only be time-consuming and cause "mixing" losses as the enrichment gradient is discontinued and reestablished but also potential loss of equipment as machines are restarted following the inventory. In cases where the process cannot be discontinued, the inventory in the process is reduced as much as possible (e.g., storage tanks are emptied) to minimize the measurement errors. Depending on the process, complex computer modeling and using multiple operational parameters such as pressure, temperatures, etc., may be necessary to calculate the in-process inventory.

For still other processes, the facility may initiate a "break" in the flow of material moving through the process. As mentioned earlier, a cutoff date and time must be established to distinguish the separation of inventory periods. At the cutoff time, all material residing in the process is credited to one inventory period, while any transfers into the process after the cutoff must be credited to the next inventory period. If the material balance process includes several steps in series, the facility may halt all transfers into the process immediately after cutoff until all the material in the first step of the process has moved on to the second step, and the first step is emptied. The transfers into the first step of the process would then resume, with credit going to the next inventory period. This material would not transfer onto the second step until all of the material from the previous inventory had moved on to the third step. This "break" in the processing steps would continue through the entire process until all of the previous inventory period's material was removed from the process and measured. Performing inventories in this fashion minimizes the amount of time the operation is disrupted during inventory.

Regardless of whether a facility tries to completely empty the process or utilizes a process break to collect the material in the process for inventory, residual amounts will still be in the process equipment. For example, in a UF_6 operation, the UF_6 may react with the processing equipment metal and form a metal oxide in the interior of the equipment, or if wet air gets into the system, the UF_6 will react to form UO_2F_2, which will be deposited inside the equipment. This holdup[77] material needs to be measured, typically by NDA,

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[77] DOE Glossary of terms.

or estimated to properly account for all of the material in the processing MBA. Similarly, material can be held up inside the actual process equipment by employing systems designed to protect the employee. For example, work with Pu or U oxides is typically done in glove boxes that have environmental systems designed to keep the glove box at a slightly lower pressure than the room. These systems will also have fans and ductwork to create this lower pressure and filters to ensure that any nuclear material dust generated is collected and not discharged directly to the environment. This ductwork and the filters are prime places where holdup material may accumulate and must be measured as part of the inventory process.

Inventory Reconciliation and Evaluation

Once the physical inventory for the MBA has been established, it is compared to the accounting records or book inventory. The book inventory is calculated by the following formula:

$$\text{Book inventory} = \text{Previous physical inventory} + \text{Increases to inventory} - \text{Decreases in inventory}^{78}$$

The difference between the ending physical inventory and the book inventory is called the MUF[79] and is determined by the following formula:

$$\text{MUF} = \text{Book Inventory} - \text{Physical Inventory}.$$

In the case of an item MBA, the expectation is that the physical inventory should equal the book inventory. If the physical inventory in an item MBA is greater than the book inventory, it is an indication of more items in the MBA than were recorded, typically indicating a missed transaction. If the physical inventory is less than the book inventory, it is an indication of a missing item, which could also be due to a missed transaction or possibly a theft of the item. In either case, an investigation will be performed to determine and resolve the cause of the irregularity.

For processing MBAs, the MUF is not expected to be equal to zero. This is due to the fact that the beginning inventory, receipts, shipments, and the ending inventory are all based on measurements that have some level of uncertainty associated with the taking those measurements. The amount of uncertainty that is expected is referred to as sigma MUF (σ^{MUF}). The limits for acceptable MUF are then typically established at two and three times σ^{MUF}. If the MUF exceeds two times the σ^{MUF} (which statistically should happen less than 5% of the time), it is in warning and could be an indication

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[78] IAEA Service Series 15. *Nuclear material accounting handbook*, Vienna; May 2008.

[79] It should be noted that in the US the term MUF is referred to as simply the Inventory Difference (ID). (DOE Standard).

of a problem. If the MUF exceeds three times σ^{MUF} (which statistically should happen less than 1% of the time), it is in alarm and is an indication of a serious problem. In either case, MUFs that exceed the two or three σ^{MUF} limit should be promptly investigated. Additionally, the MUF will be tracked and trends identified over time that could indicate a potential shift in the bias of one or more measurement systems or possibly the protracted theft[80] of nuclear material over several inventory periods.

Ideally, the σ^{MUF} would be calculated by propagating the variances (the average of the squared differences from the mean) associated with all of the measurements taken throughout the inventory period. However, in some cases, such as where in-process materials are not easily measured, the propagation of the variances can result in large σ^{MUF} values, or where measurement uncertainties are not well-defined, σ^{MUF} may be calculated as a simple percentage of total throughput[81] or active inventory.[82] The competent regulatory authority of the State will establish how facilities are to calculate σ^{MUF} and/or the maximum value for σ^{MUF}. For example, the US DOE standard states "For Category I and II, MBAs, limits-of-error (σ^{MUF}) must not exceed a 2% of the active inventory during the inventory period and must not exceed a Category II quantity of material".[83]

Investigations and resolution of MUF exceeding allowable limits will vary but may include a review of all transactions and measurement results for missing or transposed data, remeasurement of material, unaccounted-for material still in the process, and investigation of any unresolved security alarms that could indicate a possible theft of material and possibly require a complete new physical inventory of the MBA. Once the inventory reconciliation process is complete, an adjustment is made to the book inventory to bring it equal to the physical inventory. This corrected inventory then serves as the beginning inventory for the next inventory process, and the inventory cycle starts anew.

Nuclear Material Control

Nuclear material control establishes a process for authorizing and monitoring all activities for handling, processing, storing, and transporting

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[80] Theft of a goal quantity by repeated occurrences of less than goal quantity amounts., DOE Glossary of Terms.

[81] Throughput is typically defined as the larger value of the sum of receipts or shipments into or out of the MBA.

[82] Active inventory is the sum of additions to inventory, beginning inventory, ending inventory, and removals from inventory, after all common terms have been excluded. Common terms are any material values, which appear in the active inventory calculation more than once and come from the same measurement. (DOE Standard).

[83] DOE-STD-1194-2011.

nuclear material. The control measures are intended to provide defense in depth throughout the implementation of diverse and redundant approaches primarily to preclude and detect unauthorized access to, removal of, or use of nuclear material. It has the added benefit of preventing and detecting inadvertent mistakes. These approaches should be based on credible threat scenarios for the type and quantity of nuclear material in the facility with the intent of meeting the state regulations. The system should be developed in conjunction with physical protection and safety organizations.

Based on how nuclear material is stored, moved, and processed, control measures should be applied at specific points and locations within the facility to assure the highest level of effectiveness. By evaluating credible scenarios, different insider approaches will be identified. Some include, for example, accumulation of small quantities over time, utilization of shielding for removal through normal exits, and use of nonnormal exits such as process/human waste streams, ventilation ducts, maintenance hatchways, and emergency exits. For example, in facilities that have toilets within the nuclear material processing area, the sewer line might be instrumented with a radiation detector and have an intermediary collection tank since this is a potential pathway to remove material. Other approaches eliminate this potential passageway by not having any toilet facilities within the processing area.

Authorizing Personnel and Operations

An authorization process should be established for all work performed in the facility including routine and maintenance operations and the personnel who can perform these tasks. The actual authorization approval process should be limited to a small number of management personnel and be well-documented and controlled. This process must not only take into consideration daily work activities, nuclear material items, and assigned staff but the training status of the staff as well to assure they are able to perform their functions safety. This system must cover both routine and special operations. However, in order to minimize the potential of an inside adversary, the number of personnel authorized should be maintained at the lowest possible number to support the operation. Attention should be paid to appropriate controls where nuclear material in bulk form will be altered, potentially allowing a malicious insider to take the opportunity to mislabel an item and/or its value on the accountability system.

Other examples include requiring employees to have security clearances that assure background checks on criminal, financial, medical, and other factors that might help assure trustworthiness.

Access Controls

Access to specific areas of the facility would also be controlled depending on the actual work assignment so employees do not have free access to all areas. This, in turn, means that the facility has to be designed with such restrictions in mind to control access such as with a badging or a biometric system to open doors into specific areas. The application of separation of duties mentioned in the introduction is also used to assure that any employee from manager to technician has a limited span of control to reduce the probability of insider threat.

NMAC personnel working closely with the physical protection staff will identify areas where nuclear material is present and based on the category level of the Area, a graded approach for access will be established consistent with State requirements. For example, the IAEA recommends nuclear material be used or stored in at least a limited access area,[84,85] while Category I nuclear material is required to be located within a protected area[86] and an inner area[87] (sometimes called a material access area). A representation of

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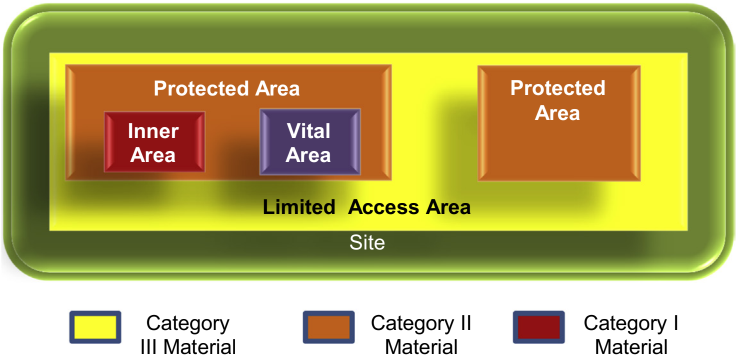
[84] IAEA Nuclear Security Series 13. *Nuclear security recommendations on physical protection of nuclear material and nuclear facilities (INFCIRC/225/REVISION 5,* 2011; p. 25.

[85] Designated area containing a *nuclear facility* and *nuclear material* to which access is limited and controlled for physical protection purposes. IAEA Nuclear Security Series Glossary Version 1.1 (May 2014).

[86] Area inside a *limited access area* containing *Category I or II nuclear material* and/or *sabotage* targets surrounded by a *physical barrier* with additional *physical protection measures*. *IAEA nuclear security series glossary version 1.1*; May 2014.

[87] An area with additional protection measures inside a *protected area*, where *Category I nuclear material* is used and/or stored. *IAEA nuclear security series glossary version 1.1*; May 2014.

the access control/protection of the various categories of material as defined in IAEA Nuclear Security Series 13 is shown below.



As one would expect, the access control and requirements become more stringent as you move through the layers towards the Category I material. For example, access to the limited area might only be controlled by ensuring only authorized personnel can enter, while access to the protected area would further restrict the number of authorized personnel and may require monitoring for contraband items, such as firearms on ingress and nuclear material and metal (which could be used to shield the radiation being emitted by nuclear material) on egress, and even further additional personnel restriction and monitoring, such as biometric verification at the inner area level.

Access to the nuclear material is not limited to just building or inner areas, but within inner areas may be vaults or rooms with additional controls to ensure only authorized personnel have access. The use of a two-person rule[88] is typically required whenever Category I material is being accessed.

The NMAC program must also control access to critical equipment such as measurement systems and the accounting database. Equipment used to obtain accountability values may be kept in controlled access rooms to ensure only authorized personnel have access, thus ensuring measurement results are not intentionally biased. Similarly, access to the accounting database should be limited to those with the need to know, and include password protection for access. For some accounting systems, access to subroutines within the accounting system may be controlled (through menus) to only those who need them.

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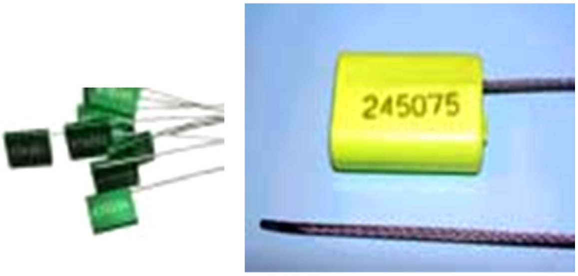
[88] A procedure that requires at least two authorized and knowledgeable persons to be present to verify that activities involving *nuclear material* and *nuclear facilities* are authorized in order to detect access or actions that are unauthorized. *IAEA nuclear security series glossary version 1.1*; May 2014.



■ **FIGURE 7.24** Multilock seals.

Tamper-Indicating Devices

TIDs are used extensively in the nuclear business to provide possible detection of unauthorized access to a container or area (cabinet, room, building, etc.). Tamper indication, in conjunction with other material control and security measures, provides assurance that an item (or area) has not been altered in some way since the last time it was inspected or since the item (or area) was made tamper indicating.[89] A wide variety of TIDs are available for use by NMAC systems. To assure effective implementation, a formal system needs to be established to control and manage TIDs in an effective and efficient manner. Besides direct applications for nuclear materials, TIDs can also be used to detect tampering with other potential pathways such as vents and maintenance hatchways and on cabinets/electronics that support monitoring of the facility.

To be used to indicate tampering, a device must have certain specific features. This may include a unique identifier as part of each device so that substitution is difficult but authentication that this is the original TID is easy to confirm; its ease of both application and removal; and ideally that its use is cost-effective. These devices have long been used to maintain continuity of knowledge on the applied item.[90] This also requires that the attachments, container, housing, room, etc., would not allow an adversary to bypass the TID. So the concept of tamper indicating must include the geometry of the item or structure being sealed.

Typical applied devices come in many different forms such as lead, metal, plastic (Figs. 7.24, 7.25), adhesive, and electronic seals. These devices and their suppliers can be found online. The type of TID used will depend on many factors, including costs. Some TIDs such as a Mylar or paper TID will have minimal cost.

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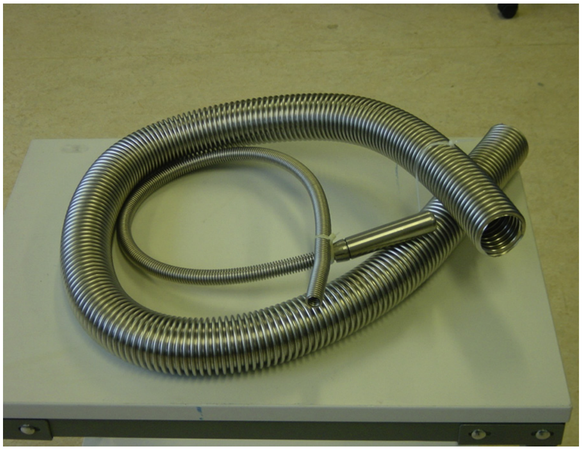
[89] DOE STD-1194-2011 Change 3; p. 38.

[90] Regulatory Guide 5.15 Tamper-indicating Seals for the Protection and Control of Special Nuclear Material, US Nuclear Regulatory Commission, Revision March 1, 1997.

■ **FIGURE 7.25** Plastic.



■ **FIGURE 7.26** Tamper-indicating conduit.

Some TIDs are unique for special applications. One example is tamper-indicating conduit that can be seen in Fig. 7.26.[91]

This conduit is used to detect potential tampering of signal cables from sensors to data collection cabinets. It is designed from stainless steel bellows and would require an adversary to cut through it and then try to cover up the penetration. This is used for analog sensors where the signal cannot be encrypted or authenticated during transmission. The inability to digitize a sensor signal in nuclear facilities is not unusual due to the risks to integrated circuits in radiation areas. But this is an expensive solution, and there is ongoing research to detect tampering on a cable using electronic means. Another unique application is tamper-indicating wallpaper. This can be used on the inside of containers with critical safeguards and security equipment.

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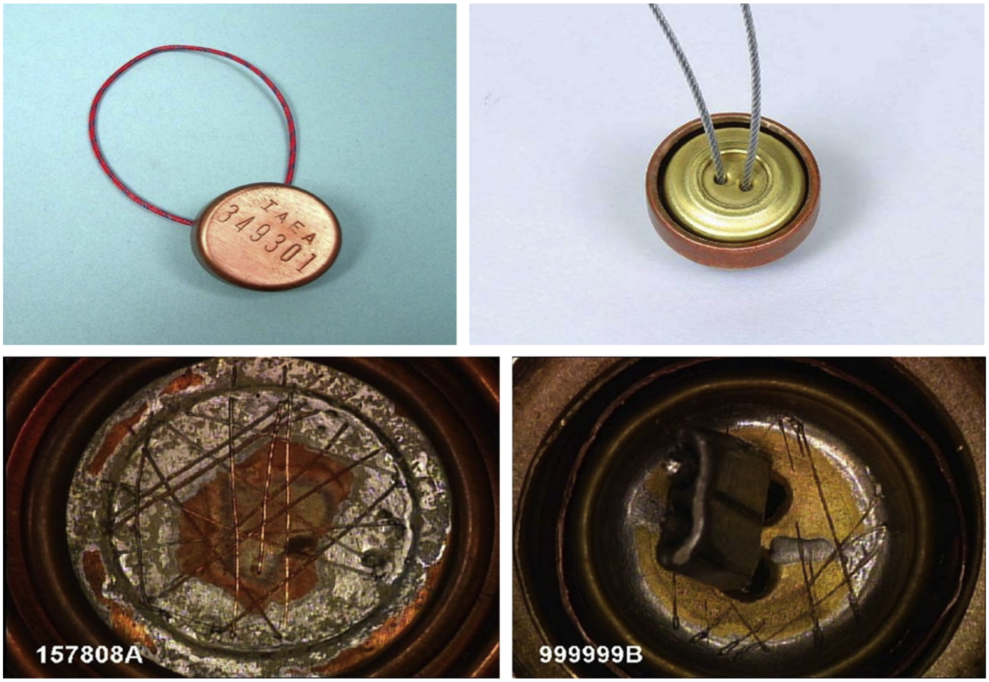
[91] *IAEA unattended monitoring systems application for data cabling from analog sensors.*



■ **FIGURE 7.27** Metal seal. *Reproduced with permission from Safeguards Implementation Practices Guide on Facilitating IAEA Verification Activities, IAEA Service Series No. 30.*

This wallpaper is extremely frangible. If an adversary attempts to penetrate the container, upon reaching the wallpaper, it will shatter, making it impossible to repair, thereby indicating a breach. These two examples are unique.

The following devices are commercially available and are currently being used by the IAEA and other regional and national programs.

The metal seal shown in the upper images of Fig. 7.27[92] (often referred to as an e-cup seal) is commercially manufactured and does not have a unique identifier that can be used for authentication. The lower images show what the IAEA does to make each seal unique. A combination of the application of solder and scratch marks by hand on the inner surfaces of the seal makes each seal unique. These two inner surfaces are then recorded as a digital image, and then the seal is released for use in the field. Upon its return, the same inner surfaces are again photographed, and a negative is overlaid over the original positive recorded image and, using auto-alignment software, is

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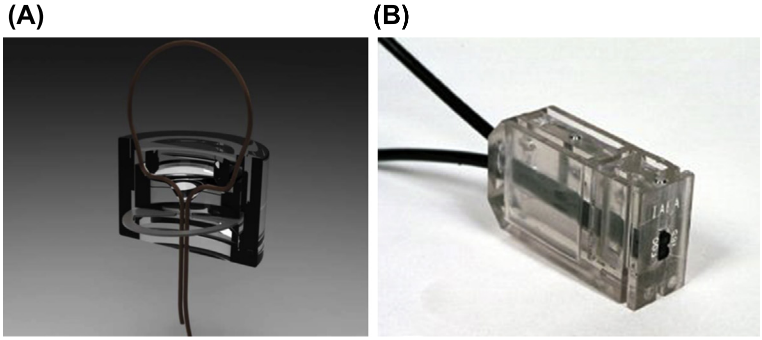
[92] *IAEA safeguards techniques and equipment: 2011 edition, international nuclear verification series no. 1 (rev. 2)*, Pg. 31.



■ **FIGURE 7.28** Glass and fiber-optic seals. (A) Glass Seal. (B) Fiber Optic Seal.

compared. It is important to keep in mind that this seal cannot be authenticated in the field. In addition, the seal wire is also an important component that has to be examined as well to assure it has not been tampered with independently of the seal.

Fig. 7.28A[93] shows a glass seal. While similar to the metal seal, it does have some unique advantages. Because it is transparent, any attempts to hide tampering of the wire internally near the exit point are now easy to see. A glass seal is also more fragile should any attempt be made to try and separate the two seal pieces. In addition, unique identifiers can be added to the glass, such as microbeads, chemical dyes, and reflective particles. Images or characteristic reflections of these unique identifiers can be captured after manufacturing and then used as a baseline of comparison to verify the seal in the field. Having results immediately in the field is always preferred in terms of a quick response to potential tampering that might indicate theft. But like the metal seal, the seal wire also needs to be examined for tampering.

Fig. 7.28B shows a fiber-optic seal. The sealing wire is composed of a bundle of fibers which are cut to length in and held by the fixture shown in the image. Under illumination, this shows a unique pattern. This image is captured using a digital camera, and the first is used as a baseline for comparison during reverification in the field. The most unique aspect is that by verifying this seal, you are verifying the seal wire, as this constitutes the sealing mechanism. Any tampering with the seal wire would cut and shift fibers, changing the unique pattern.

The seals mentioned so far are intended for a single use. But there are also electronic seals that are specifically intended to capture the history of

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[93] See footnote 92.

■ **FIGURE 7.29** Electro-optical sealing system. *Product Image courtesy of Mirion Technologies (Canberra), Inc.*

opening and closing of the enclosure like a vault storage door or cabinet. This independent record can then be compared with the operator's declared access. One example is in Fig. 7.29.[94,95] Like the fiber-optic seal, this seal also uses an optical fiber but also includes an attached battery-powered digital device that transmits light from an LED through the fiber. Whenever this is interrupted, it is recorded as an opening. When the light circuit is closed again, it is recorded as a closing. The seal device itself is tamper indicating with a recorded trigger should the case be opened. This seal can also be used to trigger an unattended monitoring system like an optical surveillance unit so a viewable record can be made of the activities related to each opening and closing. The historical record of the seal can then be downloaded to a computer. The unit is dependent on a battery, and while battery lifetimes continue to increase, this remains one potential weakness, as the knowledge of the battery life must be maintained and serviced when needed.

This concept has been taken further with the remotely monitored sealing array that can monitor hundreds of these fiber-optic seals and can be seen in Fig. 7.30.[96]

Restrictions on access to safeguards equipment and independence when access is made also involve maintenance or repair of hardware and software. This includes contractors who may be brought in the facility to work on

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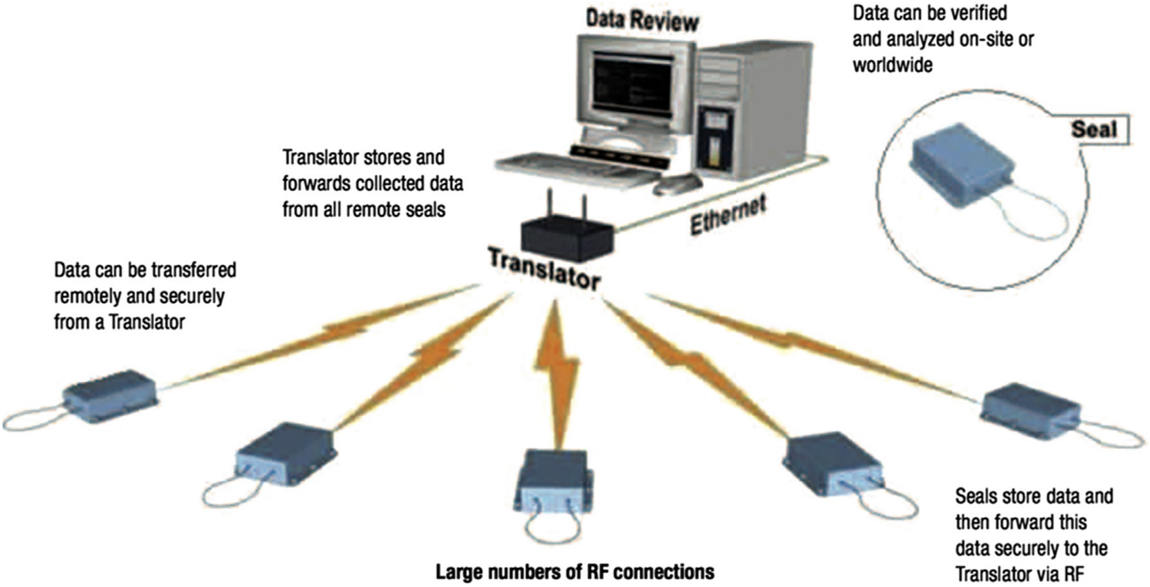
[94] See footnote 93.

[95] http://www.canberra.com/products/safeguards_surveillance_seals/pdf/EOSS-SS-C32701.pdf.

[96] http://www.canberra.com/products/safeguards_surveillance_seals/pdf/RMSA-SS-C38824.pdf.



■ **FIGURE 7.30** RMSA (remotely monitored sealing array). *Product Image courtesy of Mirion Technologies (Canberra), Inc.*

unique systems. In this case, other trusted staff must monitor such activities when unescorted access is not allowed.

The use of unalterable logs for accountability and assay entries is another method to prevent insider activities. Under this case, once a computer entry is made it cannot be erased/deleted, only a second correcting entry is possible, so the entire history of every entry is recorded.

Material Containment

The function of material containment is to ensure that the nuclear material is maintained in its assigned location, and no one has diverted or stolen the material.

Material can be contained in many forms depending on the nature of the facility and the associated safety issues, and then those forms can be contained in larger structures. Typical examples include: cans, bottles, pins, rods, storage cabinets, glove boxes, rooms, and vaults. Consideration should be given to all the credible pathways for potential removal, with monitoring added using a graded approach based on the value and form of the material. Mechanisms to maintain continuity of knowledge can be applied such as locks, seals, and alarms on doors, vent covers, maintenance hatchways, seals on containers, and surveillance on critical areas. With modern surveillance

■ **FIGURE 7.31** Hand monitoring for metal.

capabilities, specific pixel areas in an image can be used as triggers to alert security and display the recorded image as it takes place.

The use of metal detectors and radiation detectors to check for unauthorized removal of nuclear material at the inner area and protected area has already been discussed (Fig. 7.31), but what about when material needs to cross these barriers? NMAC must establish programs and procedures to ensure that only that material that is authorized is moved. This means that the program must assure that when nuclear material is moved, it is authorized to be moved and is based on a measured value and that checks are performed to ensure that only that material authorized is moved. For example, at least two personnel may be required to check the item identity and TID on the items as they leave the inner area. Similarly, measures must be in place to ensure other materials such as office waste, failed equipment, or lightly contaminated non-nuclear materials are monitored to ensure that removal of these materials do not provide a path for an adversary to covertly remove nuclear material. Waste monitoring can be a costly and time-consuming effort but is essential for ensuring containment of nuclear material.

NMAC will also work with physical protection personnel to establish systems and approaches to provide both periodic and continuous information on the status of nuclear material and other relevant equipment, with the intent to prevent or detect unauthorized nuclear material movements. These systems can include, for example:

- radiation portal monitors
- metal portal monitors
- optical surveillance

- two-person rules
- item and process monitoring
- radio-frequency identification tags
- weight and heat sensors
- motion sensors
- balanced magnetic switches

For example, we have already discussed the use of an electronic TID to trigger an optical surveillance system and transmit the image back to a central alarm station for review and, if necessary, action.

Item Monitoring

To increase the likelihood of detecting unauthorized removal of nuclear material items, periodic monitoring of items should be done between physical inventories. This can take many forms, from random statistical sampling on some periodic basis to daily administrative checks of any items that are not under seal. Checking seals, of course, should also be included in such a program. Daily administrative checks are typically carried out before the beginning of a workday or work shift to assure that all items listed on the inventory are present. This requires an accurate accountability system that is updating item location in near real time. Whatever the nature of the program that selects the item(s), the item selected can also undergo different activities such as integrity check and confirmatory measurements. This activity improves the possibility of timely detection of altered or missing items and record falsification.

Process Monitoring

As with item monitoring, the same concept should be taken of any process. Unlike items, which are static and can be individually examined, a process is dynamic with the material in a constant state of change over time. An NMAC-based analysis needs to be performed to identify the best mechanisms to detect and deter possible insider activities in a processing situation. One effective approach is to identify points where input and output materials can be quantified. As with an MBA, a sub-MBA can be established to allow for a balance to be drawn and a statistical analysis can be done to determine if any difference is significant. The use of sub-MBAs was mentioned before as a way to localize losses and gains. This approach benefits both the NMAC program and operations, as it is also a way to keep the operator informed on the efficiency of the process. Keep in mind that differences can be due to process upsets, measurement uncertainties, as well as insider activities. But whatever the cause, the sooner it is identified the better for the facility and operator.

Besides the potential to use this accounting balance approach to monitor processing, real-time instrumentation that monitors the process's nuclear material flow can also be very valuable and timely. This could mean using existing operator monitoring systems such as inline flow meters for liquids and gases, electronic balances, and tank bubblers for level and density. New instrumentation is continually under development and can be used by NMAC systems to deter and detect any attempts at theft or tampering.

Nuclear Material Movements

The term nuclear material movements can be used in a variety of ways when describing the change of location for nuclear material. IAEA Nuclear Security Series Number 25-G divides nuclear material movements into three terms: (1) receipts, for when nuclear material is received in to a facility from another facility; (2) shipments, for when material is shipped from one facility to another facility; and (3) transfers, for movements between MBAs in the same facility. The US DOE Orders and Standards do not make such a distinction, since many of their requirements for shipping and receiving nuclear material are the same whether the material is moving between MBAs in the same facility or between facilities. The US DOE will typically use terms such as internal transfers and external transfers to distinguish any differences. For defining movements in this section, the US DOE methodology will be utilized for simplicity.

Introduction

As mentioned earlier, one of the primary elements of NMAC is the establishment of MBAs and the tracking of material as it moves into and out of the facility and/or MBA. Whether it is a movement between MBAs in the same facility or transfers into or out of the facility to/from another facility, NMAC must have an established program that ensures all movements are properly documented and verified. Furthermore the movement of material between facilities must be reported to the SSAC and, if under the IAEA Safeguards Agreement, to the IAEA.[97] Failure to properly document movements will create MUFs for the MBAs/facilities involved, which must be reported and investigated.

Additionally, the movement of nuclear material poses unique challenges for physically protecting the material against theft, whereas nuclear material in storage or in process can be protected by physical boundaries that limit access; material movements take place across open spaces and thus are more

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[97] Movements between MBAs within the same facility may also require documentation to the State and IAEA based on State regulations and the IAEA agreement.

vulnerable to adversary attacks. The proper categorization of the material, based on NMAC data, is essential in ensuring that the movement is protected at the proper level. Whether the movement is within a facility, between two facilities in the same country, or across international boundaries, an effective NMAC program will have a significant contribution to the overall security of the material. The NMAC programs must work closely with the physical protection programs and protective force regimes to ensure the material is properly protected during the move and is received on time as expected.

Shipments

As mentioned in previous sections, all material being shipped from an MBA must be based on measured or technically defensible values. NMAC is responsible in not only ensuring that this requirement is met but also ensuring the integrity of the information. Thus, it can essentially be stated that the NMAC contribution to the shipment starts when the material is measured and the integrity of that measurement is protected. The proper use of material control elements, such as TIDs, two-person rules, surveillance measures, and access control elements discussed earlier, are used to ensure that no undocumented changes have occurred to the material since it was previously measured. However, in providing defense in depth, for attractive material (i.e., Category I or II materials), additional measurements may be done during the packing and loading stages of the shipment to confirm an attribute of the material, thus ensuring that the values in the accounting records are still valid.

Prior to shipment, the NMAC organization will be responsible for ensuring several key security concerns are addressed. For external shipments, the NMAC organization will need to ensure that the receiving facility is licensed to receive the type and quantity of material being shipped. For internal shipments at facilities that have multiple MBAs with different category levels of MBAs, the NMAC organization will ensure that shipments from a higher-category MBA to a lower-category MBA will not cause the receiving MBA category nuclear material limit to be exceeded.

For external shipments, NMAC will also prepare documentation (often referred to as “passport documentation”) for the shipment identifying the items being shipped, any associated TID identification, the quantities associated with each item, and the measurement uncertainties associated with each item.[98] Such documentation will be submitted to the state and, if applicable, the IAEA, once the material has moved. The NMAC organization will

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[98] Some states may waive the need for documenting measurement uncertainties for some materials of minimal quantity or low attractiveness.

also determine the category level of the shipment and work with the physical security organization to ensure the proper physical protection requirements for the shipment during transport are met. For internal shipments, the transfer paperwork may be limited to identifying the items being moved, the quantities for each item, and any associated TID identification.

The NMAC organization will also define the transfer checks, which must be performed during the loading process. As a minimum, item counts and/or item identification checks and TID identity and integrity checks will be performed and compared to the shipping paperwork. For higher category levels of material, a confirmation measurement of at least one of the items attributes may also be required. Once shipped, the NMAC organization will ensure that the facility accounting records are updated to show the removal of the material from the facility and applicable MBA.

Receipts

Nuclear material being received into a facility or MBA will be accompanied by the aforementioned paperwork. As the receiving facility, MBA is now taking ownership of the material; it is important that proper checks are performed to validate the material received against the passport documentation. As a minimum, item counts and/or item identification checks and TID identity and integrity checks will be performed immediately after the material has arrived. Once complete, the NMAC organization will document the receipt of the material, utilizing the passport data for updating the accounting records.

Additionally, depending on the state requirements and category level of the material, additional measurement of the material may be required. For internal moves, confirmation measurements may be sufficient. For external receipts, the state may require the receiver to perform more precise measurements to validate the material received is stated in the passport documentation. Typically, the state will also define a maximum time frame in which the receiver has for taking such measurements. Depending in the type of material, such measurements may be a verification measurement or an accountability measurement, as discussed in the previous section of this chapter. If an accountability measurement is taken, then the receiving NMAC organization will update the accounting records with the new value for the items.

Shipper–Receiver Difference

After the receipt measurements have been taken, the NMAC organization will perform an evaluation of the differences between the shipper's passport values and the values determined by measurement at the receiving facility.

Since all measurements come with an uncertainty, often this SRD will not be zero, and the NMAC organization must determine if the difference is statistically significant. This is done by combining the uncertainties of the shipper's measurements with that of the receiver's measurement in the following formula:

$$\mathrm{SRD} = \sqrt{\left(\sigma_S^2 + \sigma_R^2\right)}$$

where $\sigma_S =$ is the uncertainty of the shipper's measurement, and $\sigma_R =$ is the uncertainty of the receiver's measurement.

SRDs that are statistically significant must be investigated prior to use of the material. This investigation may include, but is not limited to, checking the calibration of the measurement equipment used, remeasurement of the failed item(s), review of the measurement control data for out of control conditions, typographical errors, etc. These reviews may need to be done by both the shipping organization and the receiving organization to determine the nature of the discrepancy. The regulatory authority will also be notified and, if necessary, make the final decision on which values will be used to correct the transfer documentation.

Detection, Investigation, Assessment, and Performance Testing

The detection of potential loss of control over nuclear materials is one of the primary objectives of the NMAC system. This detection could be related to a specific anomaly discovered during daily operations or the result of assessments and performance tests of the NMAC program. It is important that all anomalies be investigated thoroughly and resolved promptly, with the understanding that such an anomaly could be the result of an individual attempting to divert or steal nuclear materials. Actions to be taken upon discovery of an anomaly depend on the nature of the anomaly and can range from a simple correction of the accounting records (in the event of typographical error) to a complete suspension of operations in the case of a missing item or unexplained MUF exceeding control limits.

IAEA NSS No. 25-G identifies several anomalies (irregularities[99]) that could be indications of possible theft of nuclear material or an unauthorized act that could put material at risk. These anomalies are not an all-inclusive list but provide a general idea of the types of events/irregularities that should be investigated.

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[99] The IAEA uses the term irregularity to describe anomalies or discrepancies associated with the NMAC program.

Possible indication of unauthorized removal of material:[100]

missing item(s) or material loss;
MUF outside expected limits;
allegation of unauthorized removal;
significant difference between a measured and a recorded value of nuclear material;
statistically significant value of MUF or cumulative MUF;
damaged or broken TID;
discrepancy in a nuclear material record or report;
shipper–receiver difference that fails to meet the acceptance criteria;
failures or incidents involving nuclear material; and
overstatement or understatement of shipments or receipts.

Possible indication of unauthorized act:

item found in the wrong location;
item found unexpectedly of which there is no record;
unauthorized action involving nuclear material;
damaged container;
failure of surveillance measures;
damaged, incorrect, or missing item identification;
damage to or failure of NMAC-related equipment;
violation of the two-person rule;
discrepancy in a nuclear material record or report;
unauthorized access to data, equipment, or nuclear material;
alarm of NMAC systems, including monitoring equipment;
unauthorized operation involving nuclear material or NMAC system elements; and
violation of NMAC procedures.

Assessments and Performance Testing

Potential loss of control and other anomalies can also be detected through assessments and performance testing of the NMAC program. The regulatory body should establish a frequency for performing assessment based on a graded basis. For example, facilities that possess Category I quantities should be assessed more frequent than those with Category III quantities. Similarly, the extent of the assessment will vary based on a graded basis. Where a Category I facility may get a comprehensive assessment of all of the NMAC elements, lower-category facilities may only be assessed on one or two elements.

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[100] The irregularities listed are from IAEA NSS 25-G but have been sorted into the two separate categories for ease of understanding.

There are three different methodologies for how assessments evaluate the NMAC program. Compliance-based assessments focus on whether or not the NMAC program is performing specific **actions** identified in either the regulations or possibly documented in the NMAC plan. Performance-based assessments focus on whether or not the NMAC program is meeting specific **goals** as opposed to **actions**. The third type of assessment would be a combination of the two ensuring that not only is the NMAC program performing specific required actions but that in performing those requirements, the intent of the requirements are also being met.

For example, in the United States, facilities that are under the US NRC regulations will develop an NMAC plan, which outlines the specific actions the facility will take to meet the regulatory requirements. This plan is part of the operating license for the facility and is approved by the US NRC prior to issuance to ensure that once implemented, the facility will meet the intent of the US NRC requirements. When a US NRC assessment is performed, the facility is assessed only for compliance with the specific actions outlined in the plan. For facilities under the US DOE regulation, although the NMAC plan is also approved by the US DOE, they will be assessed against not only compliance with actions documented in the plan but also if those actions are sufficient to meet the intent of the regulation.

Self-assessments by the facility should also be done on an established frequency and a graded basis. Typically, these are more compliance-based assessments ensuring that the actions outlined in the NMAC plan are being performed as defined. One of the difficulties in conducting performance-based self-assessments is finding personnel knowledgeable in NMAC but not intimately involved in the program such that they would provide an unbiased assessment.

Performance testing is also a method of checking the status of the NMAC program elements. Like assessments, the facility should define the frequency for conducting performance tests on the various NMAC systems and MBAs. Performance testing can be as simple as functionality checks of the equipment (i.e., daily check weightings to ensure scales are functioning within tolerance), to compliance checks to ensure personnel are following procedures, to checks of NMAC personnel knowledge of actions to take (i.e., in a simulated emergency), or even to performance-based checks to ensure procedures are adequate for ensuring the intent of the NMAC requirement is being met.

There are also varying methodologies for conducting performance tests based on the objective of the element being tested. Performance tests can be as simple as observing personnel performing an NMAC function to see if they follow the procedure, to “black hat[101]” testing where an irregularity is purposely interjected to determine if the irregularity is detected and the response to the irregularity is effective. For example, the TID number on an item might be changed in the accounting records just prior to requesting an emergency inventory to see if the personnel conducting the inventory properly detect the discrepancy and then how they notify and/or resolve the discrepancy.

As is intuitively obvious, there are pros and cons for each type of testing. Direct observations are less intrusive to the operation of the facility and less costly than black hat tests but also may not provide a true measure of how personnel react or perform their duties (i.e., personnel who know they are being watched may tend to make a more concerted effort to follow procedures than when not watched). Although black hat testing may be more effective for measuring the true performance of personnel, it requires much more planning to ensure the test is realistic and that material is not put at risk during the test. Black hat performance testing can also be intrusive to operations, as it usually involves introduction of an irregularity that requires operations to stop to resolve, and can be costly, especially if compensatory measures are necessary.

CONCLUSION

A comprehensive NMAC system is a complex system that should meet the goal of providing timely and accurate information on all nuclear material activities in a facility and throughout a state. Through this capability, it should deter and detect any unauthorized access and/or activities with nuclear material. The need for overlapping detection capabilities to provide defense in depth is a testament to the high value and high potential risk of using nuclear material. An NMAC system is not a static one but one that undergoes continuous improvement through testing and the introduction of advancement of technologies and approaches. It can also evolve over time as an NMAC system matures, where a pure compliance-based regulatory approach can move to a performance-based approach. It is also one that is implemented on a graded approach that is based on the type and quantity of nuclear material used. The many elements of an NMAC system discussed here are representative of best practices at this time. The evolution to newer and better practices will continue.

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[101] Black hat refers to the auditors taking the role of the adversary to test the system.