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THE PAST - THE PRESENT - THE FUTURE

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DEVELOPMENT OF NUCLEAR MATERIALS ACCOUNTING FOR INTERNATIONAL SAFEGUARDS: THE PAST - PRESENT - FUTURE*

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ABSTRACT

Nuclear materials accountancy was introduced as a primary safeguards measure in international safeguards from the inception of the EURATOM safeguards directorate in 1959 and IAEA safeguards in 1961 with the issuance of INFCIRC 26. As measurement technology evolved and safeguarded facilities increased in both number and size, measurement methodology requirements increased as reflected in INFCIRC 66 (Rev 2.) in 1968 and later in INFCIRC 153 in 1972. Early measurements relied heavily on chemical analysis, but in the 1960s it evolved more and more toward nondestructive assay. Future nuclear materials accountancy systems will increase in complexity, driven by larger and more complex facilities; more stringent health, safety, and environmental considerations; and unattended automation in facility operations.

I. INTRODUCTION

Accounting for nuclear material under International Atomic Energy Agency (IAEA) safeguards is specifically called for in the IAEA Statute, Article XII,

> "send into the territory of the recipient State or States inspectors, designated by the Agency after consultation..., who shall have access at all times to all places and data and to any person... as necessary to account for source and special fissionable materials... ."

Safeguards in IAEA member States are applied under either of two agreements. For States not signatory to the Non-Proliferation Treaty (NPT), safeguards are applied

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under INFCIRC 66, originally published in 1965 and amended in 1968. During routine inspections, the inspection activities may include,

> "49(b) Verification of the amount of safeguarded nuclear material by physical inspection, measurement, and sampling;" and
>
> "(c) Examination of principal nuclear facilities, including a check of their measuring instruments and operating characteristics."

For States signatory to the NPT, safeguards are applied under INFCIRC 153 as published in 1971 and amended in 1972. This document is more specific in requiring measurements for the accounting of nuclear material. The operator is required to provide a

> "43(d) Description of the existing and proposed procedures at the *facility* for *nuclear material* accountancy and control, with special reference to *material balance areas* established by the operator, measurements of flow and procedures for *physical inventory* taking."

Furthermore, by paragraph 46, the operator is to identify material balance areas (MBAs) and key measurement points for accounting purposes. According to paragraph 55, "the system of measurements ... shall either conform to the latest international standards or be equivalent in quality to such standards."

The inspection activities may,

> "74(b) Make independent measurements of all nuclear material subject to safeguards under the Agreement," or
>
> "(e) Use other objective methods which have been demonstrated to be technically feasible."

Paragraph 74(e) is particularly important because it allows the Agency to use newly developed technology such as near-real-time accounting (NRTA) or other techniques to be described later in this report.

The European Atomic Energy Community (EURATOM) was created in 1957 to promote the peaceful use of nuclear energy in the member States. The EURATOM safeguards system was created in 1959. In 1973, EURATOM and the IAEA signed an agreement to implement the NPT. Because EURATOM is the State system of accounting for nuclear material in nonweapons nuclear facilities of member States of the Commission of European Communities, measurements are a fundamental part of their accounting system.

Because of the importance of materials accountancy and its required measurements, the US Department of Energy has supported research and development for international safeguards since the early 1970s. This program also supports bilateral activities with other IAEA member states in developing and testing new instruments and methods at nuclear facilities that may not be available in the US.

Since the US Nuclear Nonproliferation Act of 1978, the US Department of State has supported a program of technical assistance in safeguards (POTAS) for the IAEA. This program supports the training of inspectors and the development of specific instruments and methods for IAEA inspector use.

II. DEVELOPMENT OF MEASUREMENT AND SYSTEMS METHODOLOGY

A. Destructive Analysis

Destructive analysis has provided the basic measurement methods for nuclear materials since the inception of international safeguards. The IAEA opened a laboratory at Seibersdorf in 1961 for research in several scientific disciplines associated with nuclear energy. The safeguards analytical laboratory (SAL) was established at the same site in 1966 to analyze uranium and plutonium samples. The IAEA sponsored a panel of experts on the topic of Analytical Chemistry of Nuclear Fuels in July 1970[1] and a Symposium on Analytical Chemistry of the Nuclear Fuel Cycle in November 1971[2] to identify possible problem areas and recommend accepted methods.

The Davies-Gray method[3] became established as the method of choice for uranium analysis, and with variation is still used today. Gravimetry is used for pure samples that can be oxidized to U_3O_8. Electrometric techniques such as potentiometry, amperometry, and coulometry, developed primarily at the US, UK, and French weapons laboratories, were adapted to the commercial fuel cycle.

Mass spectrometry has become the method of choice for isotopic analysis of both plutonium and uranium.[4] It is capable of high precision when properly used but is limited by throughput. Because samples must be transported to the SAL, the resin bead technique was developed to minimize sample size and problems associated with transporting nuclear material.[5]

Recent trends in safeguards destructive analysis are directed toward automating procedures for speed, accuracy, and decreased radiation exposure.

Portable mass spectrometers are being studied to see if they would enable inspectors to perform analyses on-site. The advantage of on-site analysis is gained through some sacrifice in precision because of poorer mass resolution.

An alternative to mass spectrometry is being developed—the isotope dilution gamma-ray resin bead technique.[6] This enables inspectors to perform analyses on-site using the same resin beads as are used for mass spectrometry. The primary advantage is the simplicity of the equipment compared to mass spectrometry equipment. Precision is somewhat poorer than can be obtained at SAL, but is better than the precision that can be obtained with portable mass spectrometers. Further development of the method is taking place at Los Alamos, Tokai, and EURATOM.

Further developments in wet chemical analyses will be driven by health, safety, and waste minimization concerns. The UK is developing in-line electrometric procedures that do not require handling the sample.

B. Nondestructive Assay (NDA) Application Evolution

NDA instrumentation using neutrons and gamma rays allows the inspectors to make measurements in the field.

The earliest such instruments emphasized portability; the inspectors carried them along as part of their luggage. This had the advantage that the equipment was always under the cognizance of the Agency. The measurements tended to be used for attribute checks of items and were not required to be highly accurate. As time went on, there were requests for better accuracy and improved operational specifications, e.g., ruggedness and reliability. Because the Agency verified a wide variety of nuclear material in many physical and chemical forms, a number of instruments were developed. To support these instruments, the Agency developed maintenance, shipping, and most important, training organizations. Support programs played an important role in developing the instruments and the support functions. This continues to be the case up to the present time and should continue in the foreseeable future.

As nuclear fuel cycle facilities evolved, so did the NDA equipment. The portable instruments, such as the portable multichannel analyzer, incorporated microprocessor and CMOS battery operated technology and became more capable while weighing less. Some larger and heavier instruments (HLNC, AWCC, and UFBR) were still retrofitted to make quantitative measurements on bulk materials. Shipping these instruments became more cumbersome and they were left more frequently at a facility and stored under Agency seal. In a growing number of bulk facilities, permanently installed NDA systems were considered in the same way that surveillance cameras were installed at the facilities.

The Agency is using a mix of NDA equipment: portable, facility dedicated, and permanently installed. Most of these instruments are connected to a computer that collects, organizes, and analyzes the measurement data. Developing the software for these computer controlled instruments has become an important activity at the Agency.

Installed NDA equipment brings with it the need to authenticate the operation during an inspection. Authentication is the process to assure that genuine information is obtained for safeguards purposes using equipment for which the IAEA lacks sufficient control or knowledge. The Agency has developed and is developing the technology used in the authentication process. Often the installed equipment is operated continuously in an unattended mode and the authentication then needs to be maintained continuously. This continuous, unattended operation has saved many person days for facility operators and inspectors. It also provides radiation-based monitoring data that complement video surveillance information.

The accuracy of the measurement data for some materials has improved to the point that the data are routinely used for partial defect tests and, in some cases, are used by the Agency data-evaluation section to calculate nuclear balances and their attendant MUFs. This represents a major advance for NDA in the verification process. It opens the possibility for expanded use of advanced nuclear material accountability systems, e.g., NRTA, in international safeguards.

C. Systems Approaches

In the early years of international safeguards, accounting was performed conventionally. In item facilities, item tracking was used with the goal of detecting one missing item. In bulk handling facilities, MUF accounting was applied using the conventional MUF equation

$$MUF = I - O + BI - EI \ ,$$

where I = input,
O = output,
BI = beginning inventory, and
EI = ending inventory.

Acquiring these data requires a plant cleanout during a physical inventory. In the mid seventies it became clear that for future large bulk handling facilities (reprocessing, mixed oxide) it would be impossible to detect loss of significant quantities of nuclear material in a timely manner.

1. Near-Real-Time Accounting. In the mid seventies, the US DOE began funding a series of studies at Los Alamos to apply NRTA to mixed oxide (MOX) and reprocessing facilities for domestic safeguards.[7,8] These studies were extended to international safeguards applications in the late seventies.[9]

In 1978 the IAEA convened an advisory group meeting on safeguards for large reprocessing plants.[10] This led to the formation of the International Working Group on Reprocessing Plant Safeguards (IWG RPS), which met for three years to discuss various approaches to safeguarding the large plants planned for the eighties and nineties. Among its recommendations, the group included,[11]

> "Work needs to be continued on assessing the impact of NRTA on plant design and operating procedures," and
>
> "New procedures and techniques for physical inventory determination should be investigated. Specifically procedures which permit the accurate measurement of inventory quantities with minimum process shutdown and cleanout activities should be investigated."

In the early eighties the Japanese began R&D activities on applying NRTA at the Tokai reprocessing plant. A series of reports was published demonstrating the feasibility of NRTA, with the later studies performed in conjunction with the IAEA.[12]

The UK also initiated experiments in NRTA for a small fast breeder fuel reprocessing plant and demonstrated that timeliness and sensitivity goals could be met.[13] As a result of these experiments and work performed by British Nuclear Fuels Limited, the Thorp reprocessing plant will use NRTA as a fundamental safeguards measure.

Paper studies on NRTA were performed by the Federal Republic of Germany for the Wackersdorf facility, but studies were concluded when the plant was cancelled.

2. Adjusted Running Book Inventory (ARBI). Studies on ARBI were initiated by the US Nuclear Regulatory Commission in 1988. ARBI can be considered as a form of NRTA, differing in the way in-process inventory is determined. When similar statistical tests are applied to NRTA and ARBI data, comparable detection sensitivities should be achieved.

3. Cumulative Flux.[14] The cumulative flux technique was developed by France and extensive studies have been performed at the reprocessing plant at La Hague. The technique differs from NRTA and ARBI in that all of the in-process inventory and its uncertainty is estimated from process operating data. The method will be used at the UP-3 plant at La Hague.

4. **Batch Follow Up.**[15] Batch follow up or F BOMB was applied as a primary safeguards measure at the ALKEM MOX facility at Hanau. Input batches for the process are planned so a measurable difference exists in the plutonium isotopic composition of successive batches. Thus from input and output measurements the inspector can determine when a new batch is introduced, when the previous batch is completed, and thus the inventory associated with each batch.

III. FUTURE DIRECTIONS

The number of facilities and the quantity of nuclear materials under IAEA safeguards continues to increase. More countries are opening their nuclear facilities to Agency inspections. New plants with increased capacity and significant throughput are being constructed. Many of these facilities and their nuclear materials will be added to the IAEA safeguards inspection list. In contrast, the zero growth budget of the IAEA, emerging requirements to lower inspector and facility personnel radiation doses, and automation of facilities will require that fewer Agency inspectors will be available per kilogram of nuclear material and their access to verify the material will become increasingly more difficult and restricted.

A. Verification Activities

Agency inspectors will continue to conduct physical inventory verifications (PIVs), interim inspections, and unplanned/ad hoc inspections at facilities under their surveillance. These activities will be more effective and efficient with improved, newer generation, portable NDA instrumentation and computers that use sophisticated assay and inventory software. The current generation of NDA instrumentation and electronics used by the IAEA, such as the portable multichannel analyzer, will be significantly reduced in size but have more capabilities. New detectors, such as CsI/photodiode, that are small in size and have low power requirements will improve the capability of inspectors to carry their equipment and conduct ad hoc field measurements and attribute checks on materials in facilities.

Inspector training, instrument calibration, and measurement control will continue to be important and integral functions in the proper operation of the NDA measurement process. These functions will increase in importance as the NDA instrumentation expands to large integrated systems that incorporate NRTA capabilities.

B. Automated and Bulk Processing Facilities

Large bulk processing facilities that have high throughput will require integrated NDA measurement systems installed in-line providing continuous quantitative information for NRTA of nuclear materials. In particular, automated facilities that limit access to the process area during operations will require NDA instrumentation to be installed at the appropriate locations to provide unattended continuous measurements at critical processing areas in the facility. For NRTA to be effective, the in-line NDA systems installed throughout the facility, coupled with video surveillance, will need to be linked by secure local area networks through which they can continuously transmit their status and information to the central NRTA system computer. In these systems, authentication and reliability will take on increasing importance.

NRTA systems connected to continuous measurement instrumentation will produce vast quantities of data and require large storage systems to reliably hold the information. The difficulty in storing and sorting this data will require that sophisticated data compression algorithms be developed to reduce the collection of unneeded data. The development and application of pattern recognition, artificial intelligence, and neural net software will be needed to help inspectors review the data. In addition, the ability to combine data from a variety of measurement stations, to search for patterns in nuclear material movement, and to check the consistency of nuclear material flows through various points in a process will provide increased safeguards effectiveness. This information will complement safeguards inspection data obtained from the advanced nuclear material accountability systems.

Continuing improvements in NDA systems, instrumentation, and physics analysis techniques coupled to an integrated NRTA safeguards system with sophisticated artificial intelligence software will be required to meet the challenges facing Agency inspections of large, automated bulk processing facilities.

C. New Safeguards Approaches

Although the IAEA in most instances has adequate resources for maintaining acceptable verification of safeguarded materials, future increases in the size, complexity, and number of nuclear facilities combined with limitations on increases in inspection resources could degrade safeguards effectiveness. Anticipating these possible conditions of reduced effectiveness, recent studies have developed two alternative IAEA procedures, the zone approach and randomized inspections, for more efficiently applying safeguards resources. Although these new approaches are, in general, not now needed to attain current Agency safeguards goals, they represent potential means for addressing anticipated shortfalls in inspection resources.

1. Zone Approach. In the zone approach, MBAs in a State's fuel cycle that contain materials of similar safeguards significance, i.e., material categories [e.g., low-enriched uranium (LEU), spent fuel, or direct-use material], are combined into a single zone for purposes of closing a materials balance on this larger accounting area. Although the State's System of Accounting and Control would continue to report on the current MBA basis, for purposes of safeguards conclusions, the Agency would verify the zone balance. Resources are saved by this approach because the zone balance eliminates the need to verify intra-zone flows of material. Instead, only flows crossing the zone boundary and simultaneous inventories of material within the zone would be verified.

These resource savings should be weighed against the loss of verified information about material flows within the zone, which implies an inability to verify the facility materials balances. Instead, a positive statement about the zone balance would be the basis for a positive statement about each MBA. However, in the event of an anomaly in the zone information, localizing the anomaly to a single MBA within the zone and resolving it could require more resources than for anomaly resolution under the current facility approach.

Among the zones that could be defined according to material category are (1) an LEU zone with input transfer at the receipts area of an enrichment plant, an output transfer where fresh fuel enters the reactor core, and material inventories in enrichment facilities, fuel fabrication facilities, and fresh fuel stores at reactors; (2) a spent fuel zone with input transfer from the reactor core to the reactor spent fuel pond, output transfer from the spent fuel pond at a reprocessing plant to the dissolution tank in the separations area, and inventories of spent fuel in the reactor core, and spent fuel ponds at the reactor and the reprocessing plant or at interim storage facilities; and (3) a plutonium zone with input transfer at the dissolution tank of a reprocessing plant, output transfer where fresh fuel is moved into a reactor core, and inventories in chemical separation and storage areas of reprocessing plants, conversion plants, fuel fabrication plants, and fresh fuel storage at reactors.

Advances in technology for unattended measurements at modern automated facilities may reduce the utility of the zone approach. Because materials in automated facilities are difficult to access, in some instances, the IAEA relies on in-line NDA equipment to carry out flow measurements in an unattended mode. These accounting measures are complemented by advanced containment/surveillance methods that allow the IAEA to authenticate the integrity of the unattended measurements. Savings in inspection effort in the zone approach by eliminating intra-zone flow verification can be realized by the automated verification of flows without the need to eliminate these verification measurements.

The Agency has practical experience in applying the zone approach to the natural uranium fuel cycle used by the CANDU reactors in Canada where there are nearly simultaneous PIVs. There is also some limited experience with the zone approach for the LEU fuel cycle in the Republic of Korea.

2. Randomized Inspections. The principle of random sampling of a population and extrapolation of a characteristic of the sample to the entire population is currently applied by the Agency in verifying the integrity of items in a material stratum. Recent studies suggest that this same principle be applied to random sampling of facilities for inspection. In this instance, a positive safeguards conclusion for the randomly selected facilities would be the basis for a positive statement about all facilities in the population. In either case, for items in a stratum or individual facilities in a group of facilities, the conclusions drawn from the sample are equally valid from a statistical viewpoint.

3. Population of Inspection Opportunities. The first stage of a randomized inspection strategy consists of random selection from a population of inspection opportunities. These opportunities could include PIV, interim, or flow verification inspections at a single facility or at multiple facilities. Example populations include all PIV inspections in a State's fuel cycle facilities, all interim inspections at a State's reactors, or all flow verification inspections at a single facility. Thus, a population of inspection opportunities can include both spatial and temporal elements; for example, random selection of PIVs across a State's fuel cycle could be simultaneous in time but spread across multiple facilities, whereas randomized flow verification at a single facility involves just one physical location with opportunities spread over time.

4. Inspection Timing. Choice of the time to carry out a randomly selected inspection can be based on a preplanned schedule from which opportunities are selected randomly or on an unannounced basis at times that are unknown to the inspected facilities. Currently, planning for inspections of facilities is based on a six-month schedule of times when PIV, interim, and other inspections will be carried out. This schedule is negotiated with States to accommodate a facilities operation schedule. This coordination is essential in those instances such as a core change in a reactor that presents the only opportunity for making an inventory of all the material at the reactor.

A schedule could be the basis of a randomized inspection strategy in which opportunities are randomly selected from the scheduled dates for inspection. Under this regime, the facility operator would know the dates of potential inspections but not those to be actually implemented. This procedure has the advantage of accommodating the operator's need to make preparations such as access to facility areas, inventory listings, or retrieval of material.

Alternatively, the time of the inspection could be chosen randomly with no notice to the operator. These so-called short notice random inspections (SNRI) have been successfully employed for flow verifications at a fuel fabrication facility and for inspections to detect highly enriched uranium production in centrifuge enrichment plants. However, where the inspection activities require substantial preparations by the operator, the SNRI strategy may not be feasible.

5. **Method of Randomly Selecting Inspections to be Implemented.** Within the framework of either an announced schedule of inspection opportunities or an unannounced schedule of possible inspection times (for example, short notice random inspections), there should be a mechanism for selecting some fraction of these opportunities for implementation. Beginning with a specified fraction α of the inspection opportunities to be carried out, two methods are proposed for this selection: (1) at the beginning of an inspection period, randomly select the required fraction α from the inspection opportunities for implementation or (2) as the time for each inspection opportunity arrives, randomly decide to implement the inspection with probability p. The latter method results in a fluctuation of the number of inspections actually carried out in each inspection period.

6. **Operational Consideration Related to Randomization.** The principal operational change under a regime of randomized inspections is an increased need for confidentiality in the inspection planning process. Because knowledge by a facility operator that a planned inspection would not be carried out invalidates its deterrent effect, confidentiality of the planned inspections is essential to ensure the validity of safeguards conclusions based on randomization. The operational implementation of confidentiality in inspection planning conflicts with the need for an inspector to arrange visas, travel, ship equipment, and so forth before an inspection. Presence or absence of these activities would disclose the intent with respect to the inspection. Alternatives for maintaining the deterrent element for inspections not carried out are to complete all aspects of planning as if the inspection were to be done or to keep the absence of planning confidential.

At some time before the date of a planned inspection that is not to be implemented, it would be necessary to inform the facility operator of that fact. To ensure that disclosure of the inspection plan does not invalidate the safeguards conclusions based on random sampling, it is essential that the facility operator commit to a physical inventory listing describing the status of materials before the notification of intent by the inspectorate. In practice, this could be accomplished by telexing such a list a few days before the planned inspection date or using a "mailbox" at the facility that would automatically date the declaration and prevent subsequent alteration.

Where inspections are randomly selected from the six-month schedule of some fraction α of the planned inspections that are to be actually implemented and that fraction is not confidential, completion of the fraction α before the end of the six-month period discloses the absence of inspections for the remainder of that period. This deficiency is remedied by keeping the fraction α confidential or by independently deciding with probability p whether to carry out a planned inspection. Although the latter tactic would cause the total fraction of inspections carried out to fluctuate around α, it avoids prematurely disclosing inspection plans.

Frequently, facilities to be inspected are divided into geographically close clusters with facilities in a cluster inspected during that inspection tour. This procedure might restrict the benefits of randomized inspections at facilities within the same cluster because the biggest resource expenditure, inspector travel to the cluster, would not be saved. For example, if there are several facilities in a cluster and a randomized inspection plan selected only one facility for inspection, traveling to the cluster for one inspection would reduce the efficiency gained by the clustering principle.

7. **Surveillance.** Among the inspection activities carried out by the Agency, surveillance is most sensitive to interference by randomization. Indeed, for facilities such as LWRs where an inspection was not carried out, the failure to retrieve and evaluate the surveillance record would result in not attaining the timeliness goal as currently defined in the SIR criteria. Further, because the criteria require a reverification of the inventory when surveillance is not successful for any three-month period, there would be an additional inspection resource requirement that would reduce the savings gained by randomizing.

Surveillance could accommodate randomized inspections through technology advances that would extend the current three-month maximum interval for unattended operation of the surveillance device. Methods for achieving a longer surveillance period are using multiple closed-circuit television (CCTV) units and automatically sequencing the initiation of recording by each unit; increasing the storage capacity of the CCTV devices by using optical disk storage media; introducing front-end processing of surveillance data and selectively recording only those scenes in which motion has occurred; randomly increasing the interval between recorded images to extend the recording life of the medium, or developing units that can continue to record over previously recorded images when the tape has been completely used. All of these technological options allow the inspector to randomly eliminate some inspection while maintaining continued surveillance until the next inspection.

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