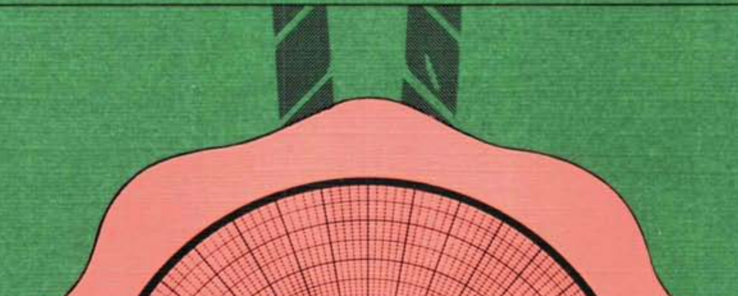
IAEA/SG/INF/6

IAEA SAFEGUARDS

IMPLEMENTATION AT NUCLEAR FUEL CYCLE FACILITIES



INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1985

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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FOREWORD

The IAEA Safeguards Information Series of booklets (IAEA/SG/INF) is intended to provide information on safeguards and related subjects with the aim of improving understanding of the methodology and practice of this unique international verification system. Booklet IAEA/SG/INF/3 attempted an overall survey as an introduction to the subject and IAEA/SG/INF/4 described the aims, limitations and achievements of IAEA safeguards within the framework of international non-proliferation efforts. The present booklet is of a more technical nature and discusses in a systematic manner the safeguards concepts, methods and approaches at various nuclear fuel cycle facilities.

The booklet replaces an earlier survey of the status of IAEA safeguards prepared for the working groups of INFCE (International Nuclear Fuel Cycle Evaluation). In order to keep the presentation concise, highly technical details have been omitted. The interested reader is referred to the IAEA Safeguards Glossary (IAEA/SG/INF/1) for the definition of some of the important terms that will be found in the text.

CONTENTS

1. CONCEPTS

1.1. PURPOSES OF IAEA SAFEGUARDS

IAEA safeguards are one important instrument of international non-proliferation policy (see the information booklets [SGI/3] and [SGI/4][1]). Their implementation is regulated by the IAEA Statute [ST] and individual safeguards agreements. Such agreements concluded by the IAEA are based on documents INFCIRC/66 [66] or INFCIRC/153 [153]. Paragraph 46 of [66] states:

> "The purpose of safeguards inspection shall be to verify compliance with safeguards agreements and to assist States in complying with such agreements and in resolving any question arising out of the implementation of safeguards."

Paragraph 2 of [153] stipulates that safeguards will be applied to nuclear material

> ". . . for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices."

These provisions place the emphasis on the role of IAEA safeguards as a *verification system.* The IAEA's independent verification activities provide assurance, at the request of a State or group of States, and of the international community, that the States are complying with their commitments concerning the peaceful uses of nuclear energy. Thus, the IAEA acts in the interest of the international community as an objective international auditor. The assurance contributes to dispelling distrust among States: the existence of such distrust could, in itself, be a motive for a State to consider the acquisition of nuclear weapons.

At the same time, safeguards serve as a warning system and as a deterrent to diversion because they introduce the risk of early detection [153/para.28]. This, of course is of relevance in very few cases, if any, in reality. After all, States conclude safeguards agreements on their own initiative and not to deter themselves. They are genuinely committed to the peaceful use of nuclear energy and they wish to contribute to the building of international confidence.

The Director General of the IAEA reports annually to the Board of Governors on the results of the IAEA safeguards activities and provides information which enables the Board to assess the effectiveness and efficiency of the safeguards system. He also reports annually to the General Assembly of the United Nations. Should any case of suspected non-compliance with the requirements of non-proliferation arise, the Director General would inform the Board

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[1] Abbreviations in square brackets are references to the publications listed in the Bibliography.

of Governors. They, after satisfying themselves that there was a case to answer, would inform the Member States of the IAEA and also the Security Council and General Assembly of the United Nations [ST/Article XII.C.]. The same would apply in those cases where the IAEA was unable – owing to technical or other circumstances – to verify that there had been no diversion of nuclear material [153/para.19]. It would then be up to the Member States and the international community to decide what response should be made or action taken.

While safeguards should attain their purpose at minimum cost, i.e. with high *efficiency,* they must also be *credible,* meaning that they must both be *effective* and *be perceived to be effective.* Objectivity and impartiality are other necessary elements of this credibility.

1.2. SCOPE OF IAEA SAFEGUARDS

The scope of IAEA verification activities is defined by the relevant safeguards agreements. Under agreements drawn up in accordance with [66], nuclear and other materials, services, equipment, facilities and information may be subject to safeguards and the aim of the IAEA verification is to ensure that they are not used in such a way as to further any military purpose. The safeguards activities of the IAEA in these cases are limited to the specific items placed under safeguards. Any unsafeguarded activities which might involve the use of these items are taken into account in the design of the safeguards approach.

Under agreements concluded pursuant to [153], the principal object of safeguards is nuclear material rather than nuclear facilities. Thus, the verification activities are intended to provide assurance that the material in question is not diverted from peaceful uses to the production of nuclear weapons or other nuclear explosive devices, or to other purposes unknown. The main difference between [66] and [153], however, is the full-scope intent of the latter [153/para.1], whereby the State accepts safeguards on *all nuclear material* in all its peaceful nuclear activities. It is the IAEA's right and obligation to ensure that safeguards will be applied, in accordance with the terms of the agreement, to all such material [153/para.2]. The agreement contains safeguards procedures to be followed by the IAEA to ensure compliance with the basic commitment by the State, namely not to divert nuclear material. However, no specific procedures are foreseen for verification by the IAEA of the second commitment, namely that the State should submit all nuclear material to safeguards, and in particular for the verification of the completeness of the initial inventory report. This omission is both noteworthy and easy to understand. The Statute does not allow the possibility of the IAEA undertaking to search out clandestine nuclear activity in Member States. The rights and obligations of the IAEA with respect to the full-scope commitment under [153] are therefore restricted to verifying, within the limits set by the safeguards agreement, that nuclear facilities accessible to IAEA safeguards are not connected by a nuclear material flow to other nuclear activities which might exist and which – in violation of the agreement – were not submitted to IAEA safeguards. Technically this is part of the normal verification procedures at facilities submitted to IAEA safeguards (see Sections 2.2 and 2.4).

Safeguards agreements are complemented by Subsidiary Arrangements which describe in more detail the technical and administrative procedures for implementation of the agreement. Under [153]-type agreements, the general part of the Subsidiary Arrangements is applicable to all nuclear activities in the State concerned. For both [153] and [66], specific procedures for each facility and for other locations where nuclear material is present are specified in Facility Attachments.

1.3. THE CONCEPT OF VERIFICATION

Verification is a technical activity aimed at achieving the political purposes of IAEA safeguards, namely assurance and deterrence. Under the circumstances indicated in Section 1.1 above, the normal result of IAEA verification is assurance of compliance by States with their non-proliferation commitments. However, IAEA findings are credible only if verification activities are so thorough that non-compliance (diversion of nuclear material, misuse of facilities, etc.) would be detected with high probability. Therefore, in developing an effective verification methodology, the IAEA has to assume as a general working hypothesis that non-compliance cannot be excluded and that consequently a diversion risk of low but non-zero probability exists in all countries[2]. If careful verification activities lead to the conclusion that the diversion hypothesis cannot be substantiated, then it can be concluded with a high level of confidence that in fact no diversion or misuse has occurred[3].

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[2] This should not be misunderstood as an expression of distrust directed against States in general or any State in particular. A comparison could be made with the philosophy of airport security. In order to be effective, airport security measures have to assume a priori and without any suspicion against a particular passenger that each bag might contain prohibited items.

[3] This interpretation of verification in the context of international safeguards is also contained implicitly in [153/para.19] which covers the case where the IAEA is unable to verify that there has been no diversion of nuclear material.

Conceptually, IAEA verification can thus be regarded as the testing of diversion hypotheses[4]. Analysis of such hypotheses is therefore an important means for designing and organizing effective and credible verification activities. In the analysis, a wide range of potential diversion strategies and possible concealment methods have to be considered in connection with all types of nuclear material and facilities. The diversion analysis includes a consideration of the characteristics of the nuclear facility, the type and location of material, and possible diversion paths, diversion rates and concealment methods (see Section 2.2).

It would, however, not be very realistic to consider scenarios in which a specific act of diversion was actually witnessed as it occurred. Rather, it is the purpose of the diversion analysis to identify anomalies, that is to say 'observables' that may be indicative of acts of non-compliance[5]. The various safeguards approaches are thus designed to ensure that verification activities are capable of leading, with a high probability, to the timely detection of such anomalies; and to define such further activities as are needed to determine the causes of the anomalies.

There may be different reasons for the occurrence of anomalies. In general, they result from entirely innocent causes such as recording or measurement errors. However, they could also be the result of diversion or misuse. As a consequence, the IAEA as part of its verification work undertakes follow-up activities intended to resolve each observed anomaly and to ensure that no true cause for alarm is ignored or false alarm raised. If all observed anomalies are satisfactorily explained, the IAEA can state as an objective fact that during the given reporting period no anomaly that would indicate diversion was detected. The thoroughness of the verification methods applied would then permit one to conclude with a high level of confidence that no such anomaly in fact existed and therefore that no diversion of the kind considered in the diversion hypothesis had occurred.

1.4. TECHNICAL OBJECTIVES OF IAEA SAFEGUARDS

For practical purposes it is necessary to go beyond the general concepts discussed in Section 1.3 and to define more specifically the technical objectives of IAEA safeguards. Document [66] does not contain explicitly formulated technical objectives. However, specific approaches have been developed in the

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[4] Owing to the emphasis on nuclear material in [153]-type agreements and its prominent place in [66]-type agreements, and in order to focus in this booklet on the predominant safeguards situations, we will deal mainly in the following pages with the diversion of nuclear material.

[5] Examples of anomalies might be: nuclear material or equipment missing, inaccessibility of nuclear facilities, IAEA seals tampered with, inconsistencies in documents, etc.

practical process of devising and applying verification procedures for cases covered by [66]-type agreements. The experience thus gained has been used in the formulation of the technical objective of safeguards agreements concluded pursuant to [153]. This objective is stated explicitly in [153/para.28]:

> ". . . the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosives or for purposes unknown . . ."[6]

1.4.1. Detection goals

For the careful planning of safeguards implementation and for objective performance evaluation, it is necessary to quantify the terms used in the above quotation. The various numerical parameters (significant quantity, detection time, detection probability), together with a further parameter known as the false alarm probability, constitute the so-called detection goals. These parameters cannot be deduced solely from physical and technical axioms and reasonable values have been selected on the basis of technico-political judgement and consensus. The present detection goals are discussed in detail in [SGI/4] and numerical values are given in [SGI/1].

The *significant quantity* (SQ) is defined as the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded. Typical values of an SQ (not to be confused with critical mass) range from 8 kg of plutonium to 20 t of thorium.

The second parameter, *detection time*, should correspond in order of magnitude to the conversion time, estimated as the time necessary to convert different forms of nuclear material to the metallic components of a nuclear explosive device. Conversion time values used at present range from 7 to 10 days for metallic plutonium to one year for natural uranium.

For planning nuclear material accountancy measures in accordance with common statistical practice, a *detection probability* of 90–95% and a *false alarm probability* of less than 5% are used. The thorough evaluation or investigation that is made of observed anomalies results in a decrease of the final false alarm probability to far below this value.

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[6] The inclusion of the expression "for purposes unknown" is very important for the practical application of safeguards, because it means that the IAEA does not have to attempt to determine the use to which diverted material is put and, in particular, does not have to determine whether nuclear material is diverted to the manufacture of nuclear weapons or other nuclear explosive devices.

1.4.2. Inspection goals

In planning the inspection regime for particular nuclear facilities, the detection goals are not used in a purely mechanical way; they are not interpreted as rigid requirements but as guidelines to be used in designing safeguards approaches and establishing *inspection goals.* The latter reflect actual conditions at the facility, the requirements of the safeguards agreement, the limitations of measurement methods, and the effectiveness of given safeguards procedures and techniques. They are thus performance targets adopted for a given facility and they provide a basis for designing the appropriate safeguards approach. Inspection goals are established with their attainability in mind and are in fact, as the records show, attained at many facilities of various types. The achievement of goals in other, more difficult, cases will depend, inter alia, on the resources available to the IAEA.

The *accountancy verification goal* (AVG) is the minimum quantity of nuclear material which, if diverted at a facility, should (to the required degree of probability) be detected by the application of nuclear material accountancy measures alone with a low risk of false alarm. In the case of item facilities (see Section 2.1.1) the goal is equal to one SQ of nuclear material, including that which might be produced as a result of unreported irradiation. In the case of bulk handling facilities (see Section 2.1.1) the goal depends, inter alia, on the nature of the facility, the quantities of material handled, and the effect of measurement uncertainties. For most current bulk handling facilities it is also possible to set the accountancy verification goal equal to one SQ or less.

The *timeliness goal* is a parameter derived by adapting the detection time guidelines to the specific conditions at a facility. It also reflects the available safeguards resources. The timeliness goals currently used for determining the frequency of inventory verification and containment and surveillance activities (film evaluation, seals examination, etc.) at facilities handling one SQ or more of nuclear material range from up to four weeks for material containing high enriched uranium (HEU) or plutonium in non-irradiated form to twelve months for low enriched uranium (LEU) or natural uranium.

It must be emphasized that detection goals are only one of several factors determining the inspection goals. The use of inspection goals which in some cases do not meet detection goals should not be seen as a failure of safeguards. Inspection procedures aiming at an inspection goal of more than one SQ still provide a possibility of timely detection of the diversion of one SQ or less, but with lower probability.

The successful implementation of safeguards and the extent to which inspection goals can be achieved depend largely on the degree of co-operation offered by the State and the facility operator concerned and on the availability of manpower, safeguards equipment and inspection support services. The extent to which Subsidiary Arrangements made under safeguards agreements provide the IAEA with the necessary rights is also an important factor.

Characteristic inspection goals will be listed later for the various types of nuclear facility.

1.5. CO-OPERATION WITH THE STATE

Effective implementation of safeguards requires co-operation between the IAEA and the State concerned. To this end, agreements of the [153] type require that the State shall establish and maintain a system of accounting for and control of nuclear material subject to safeguards (SSAC). They prescribe that the system shall be based on a structure of material balance areas (MBAs, see Section 2.1.1) and shall provide for the establishment of a measurement system, a records and reports system, procedures for taking physical inventories, and provisions to ensure that the accounting procedures and other arrangements are being correctly operated [153/para.32]. This should enable the IAEA to verify the findings of the SSAC. In performing its verification, the IAEA takes due account of the technical effectiveness of the SSAC [153/para.7].

Document [66] does not explicitly refer to an SSAC or to all of the above elements of such a system, but it does prescribe the accounting and operating records that have to be kept by the facility operators and the accounting and operating reports that have to be submitted by the State to the IAEA.

Both documents, [66] and [153], require that the State make information available to the Agency. Specifically, they require the State to:

- Provide the IAEA with information in respect of facility design features and other information relevant to safeguards
- Arrange for the keeping of records for each facility or MBA
- Provide the IAEA with reports in respect of nuclear material, based on the records kept.

On the basis of co-operation with the State concerned, the verification process involves three main areas of inspection activity:

(1) The *examination* of the information provided by the State, including:

  - Design information
  - Accounting and operating reports, and special reports
  - Amplification and clarification of reports
  - Advance notification of international transfers.

(2) The *collection* of information by the IAEA through:

  - Visits for the verification of design information
  - Ad hoc and routine inspections
  - Special inspections.

(3) The *evaluation* of the information provided by the State and collected during inspections for the purpose of determining the completeness, accuracy and validity of this information.

The results of inspections performed under [153]-type agreements are reported by the IAEA to the State concerned in the form of a statement which identifies the inspection and the detailed activities carried out. Also noted are any discrepancies and anomalies, together with their significance and the results of an investigation into their cause. This kind of statement is of a preliminary nature because evaluation activities may still be under way and usually more than one inspection is made before a conclusion is drawn.

After the physical inventory taking (PIT) by the plant operator (see Section 2.1.1) and the physical inventory verification (PIV) by the IAEA, a second type of statement is sent to the State, containing the conclusions drawn from the safeguards activities performed. This includes a statement in respect of each MBA of the amount of material unaccounted for (MUF, see Section 2.1.1) over a specific period (the material balance period, MBP) for each category of nuclear material [153/para.90]. The statement shows whether the material subject to safeguards has been satisfactorily accounted for during the period between PIVs. If the IAEA is not satisfied with the results obtained during inspections, further investigation is called for and the State is requested to examine the causes of any inadequacy and undertake the necessary remedial steps.

Statements made to the Member States with regard to safeguards applied pursuant to [66]-type agreements record the results of each inspection.

A more detailed description of the role and functions of an SSAC can be found in [SGI/2].

2. METHODOLOGY

2.1. SAFEGUARDS MEASURES

According to paragraph 29 of [153], nuclear material accountancy (NMA) is a safeguards measure of fundamental importance, with containment and surveillance (C/S) being important complementary measures. Document [66] also relies on an accountancy approach, but it does not contain explicit provisions for C/S measures. In more recent safeguards agreements based on [66] there is an explicit provision of C/S measures and these are agreed to in the Subsidiary Arrangements. The reliance on NMA and C/S does not exclude the application of other objective measures, such as the use of conclusions drawn from verification of the operational status or the design reverification of a facility.

IAEA verification activities can be carried out in practice only with the substantial co-operation of the facility operator and the State concerned, as described in Section 1.5. This co-operation is necessary for implementation of the following basic concepts (see [153/paras 6, 7, 72, 74, 75, 79, 90]):

- The independent verification by the IAEA of the entire State accountancy system for nuclear material by means of document audits, item counting and identification, observation, chemical analysis and non-destructive measurements, seal verification, etc.
- The periodic closing of material balances by the taking of physical inventories by the operator and their verification by the IAEA
- The effective monitoring by the IAEA of the flow of nuclear material through the use of instruments and other techniques at key measurement points and other strategic points
- The use of C/S as important complementary measures.

2.1.1. Nuclear material accountancy (NMA)

Nuclear material accountancy relies on the principle of conservation of matter. Any changes to the inventory of material present in a defined area must be equal to the net production or loss of such material within the area plus the inward flow of such material from outside, minus the flow out of the area. Effective verification based on this principle requires knowledge of the flow and inventory of the nuclear material and the compilation of periodic nuclear material balances.

Areas defined in nuclear facilities for application of the conservation principle are called material balance areas (MBAs). Their delineation takes account of the specific technical aspects of the nuclear facility and their boundaries are chosen to facilitate the measurement of all nuclear material transfers across the boundaries and the establishment of the inventory within the MBA. Measurements are made at certain strategic points (SP), called key measurement points (KMP), which are locations where information on flow and inventory can be gathered and verified and at which nuclear material appears in a form in which it may be measured.

An NMA cycle starts with the determination by the operator and verification by the IAEA of the physical inventory for an MBA (see also [SGI/3]). The operator maintains a book inventory based on the initial physical inventory, adding increases (e.g. receipts) and deducting decreases (e.g. shipments)[7]. The

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[7] The accounting activity of the operator is to be documented in accounting records and operating records, complemented by supporting documents such as measurement results, irradiation data, shipping documents, etc.

NMA cycle is closed by an ending PIV and by evaluation of the material balance for the period considered by the operator: both are verified by the IAEA.

The analysis of nuclear material samples taken at the facility is a vital part of the verification process. Some analyses are carried out during IAEA inspections without physically affecting the item under examination, i.e. by non-destructive assay (NDA). Some samples have to be measured by 'destructive' techniques, such as chemical and other analyses. This is done in the IAEA Safeguards Analytical Laboratory.

For facilities handling identifiable 'items' containing nuclear material (e.g. fuel assemblies or sealed containers), the integrity of which can be considered as preserved during the NMA period, no difference between the updated book inventory and the ending physical inventory is normally to be expected. For facilities with nuclear material in unsealed bulk form (powder, pellets, solutions, scrap, etc.), there is always some difference between the book inventory and the physical inventory because of the unavoidable limitation on the exactness of measurements. There may also be discrepancies for other reasons, e.g. failure to measure parts of the inventory, unmeasured loss of material and, conceivably, diversion. The difference between the book inventory and the physical inventory represents the material unaccounted for (MUF). Because MUF is a quantity derived from measurements, it may be used as an indicator in evaluating the possibility of diversion.

On the basis of operators' NMA activities, the State submits periodic accounting reports to the IAEA, namely:

- *Inventory Change Reports* (ICR), which describe each increase and decrease of nuclear material in each MBA since the last report; and
- *Material Balance Reports* (MBR), accompanied by Physical Inventory Listings (PIL) submitted after each physical inventory and containing the MUF analysis.

On the basis of these reports, the IAEA maintains a set of accounts parallel to that of the State, and subjects the facility records and State reports to audit and comparison with its own records.

IAEA verification activities are described more fully in Section 2.4.

2.1.2. Containment and surveillance (C/S)

Containment and surveillance measures are widely used in IAEA safeguards to complement and support NMA. It is the purpose of C/S measures to provide information on movements of nuclear material or on the integrity of equipment, verified data, etc. In many instances they cover the periods when the inspector is absent and thus contribute to cost-effectiveness. Containment and surveillance measures are for instance applied:

- to ensure during flow and inventory verification that each item is inventoried without duplication and that the integrity of samples is preserved
- to ensure that IAEA instruments, devices, working papers and supplies are not tampered with
- to reduce the need for repeating the verification of previously verified items or of containers the integrity of which has not been changed
- to cover specific safeguards situations[8].

Containment measures take advantage of existing structural features, such as containers, tanks, pipes, or substantial walls, to establish the physical integrity of an area or item by preventing the undetected access to or movement of nuclear material, or interference with equipment or data.

Surveillance refers to both human and instrumental observation aimed at indicating the movement of nuclear material, or interference with containment or IAEA equipment. It thus serves to assure the integrity of containment. Surveillance may also be used for observing various operations or obtaining relevant operational data. It may involve, for example, the checking of tamper-indicating seals and the use of automatic surveillance systems (ASVS), such as camera or closed circuit TV systems, or radiation and motion monitors applied by the IAEA. IAEA inspectors may fulfil similar assignments continuously or periodically at strategic points.

The C/S techniques used by the IAEA are carefully designed and implemented to avoid imposing any unnecessary physical restrictions on facility operations or movements or access to materials which are in accordance with the design information and which are duly recorded and reported. Nevertheless, they must provide the IAEA with credible information on whether unreported movement or access might have occurred or whether the integrity of data might have been impaired. The detection of an anomaly relating to C/S measures does not necessarily by itself indicate that material has been removed. The ultimate resolution of C/S anomalies (e.g. broken seals) is provided by NMA measures (e.g. the reverification of the material under seal).

If any C/S measure has been, or may have to be, breached, the IAEA must be notified by the fastest means available. Examples might be seals which have been broken inadvertently or in an emergency, or seals for which the possibility of removal after advance notification to the IAEA has been agreed between the IAEA and the operator.

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[8] Examples might be: on-load refuelled reactors, where the fuel in the core is not routinely accessible for inventory taking, and situations where a safeguarded nuclear reactor is routinely supplied from an unsafeguarded fuel fabrication plant.

2.2. DIVERSION ANALYSIS

The necessity of analysing potential diversion strategies and concealment methods and identifying related anomalies has been discussed in Section 1.3. An important element of diversion strategies at the facility level is the variety of possible diversion paths, each characterized by the amount, type and location of nuclear material involved, the physical route the material follows, any conversion of the material that takes place, the rate of removal and the concealment methods applicable.

With regard to the physical route and conversion of nuclear material the following main categories are considered:

- unreported removal of nuclear material from a facility or from transit
- unreported introduction of nuclear material into a facility, including the case where the material might originate from a facility not submitted to IAEA safeguards[9]
- unreported transfer of nuclear material between the MBAs of a facility
- any kind of unreported modification of nuclear material (e.g. production of plutonium from fertile material, or enrichment of uranium beyond the authorized level[9])
- proscribed uses of the material within the facility[10].

With respect to the amount of nuclear material that might be diverted in a given time (the diversion rate), the continuum between the following two limiting cases is considered:

- one SQ or more in a short time, e.g. within the conversion time for metallic plutonium (abrupt diversion); and
- one SQ or more per year, for example by accumulation of many small amounts in a fuel fabrication plant (protracted diversion).

Concealment methods to be taken into account may include:

- restriction of access of inspectors to agreed areas by simulated difficulties
- falsification of records, reports and other documents by overstating inventory decreases (e.g. shipments) or by understating inventory increases (e.g. receipts)
- temporary replacement of diverted nuclear material with material 'borrowed' from other MBAs or taken from unreported stocks
- replacement of diverted nuclear material with material of lower safeguards significance (e.g. dummy fuel assemblies)

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[9] These assumptions are discussed in [SV].

[10] Diversion of nuclear material from peaceful uses does not necessarily mean removal of the material from a facility.

- falsification of measurements or of their evaluation ('diversion into MUF')
- interference with containment or with IAEA seals or equipment.

As a result of diversion and its concealment or other unintentional actions, anomalies will occur. The first group of anomalies is connected with access and facility conditions. Examples are:

- refusal to allow inspectors access to the State, to the facility or to agreed areas, or obstruction of inspection activities
- non-accessibility due to safety problems (e.g. high radiation background)
- significant changes of facility features or of the operating mode of a facility without the required prior notice.

These types of anomaly are self-evident and trigger appropriate action by the IAEA, including a report to the Board of Governors.

Another group of anomalies is related to NMA measures, i.e. it is expected that the relevant inspection activities described in Section 2.4 would reveal them. Typical examples are:

- departure from the agreed records/reports system or non-availability of relevant documents
- records and reports being incomplete, inconsistent or incorrect
- considerable differences between the amounts of nuclear material present as reflected in the records or reports and as determined by inventory verification
- lack of agreement between the composition, enrichment, or irradiation status of nuclear material as reported and the verified values.

Anomalies related to C/S measures as described in Section 2.4 usually result in loss of continuity of knowledge of the nuclear material inventory and flow. In such cases it is necessary to re-establish the necessary knowledge, for example by a physical inventory of the items concerned. Examples of this kind of anomaly are:

- seals damaged, tampered with, or detached without prior notification
- failure of surveillance due to loss of light, obstruction of view, etc.
- unexplained movements of nuclear material
- significant change of the containment structure (e.g. penetration)
- interference with IAEA equipment
- failure of IAEA equipment or inconclusiveness of films or tapes.

2.3. INSPECTIONS

The key to verification by the IAEA is the right to conduct on-site inspections. Three types of inspections are involved: routine and special inspections in accordance with [153] and [66], and ad hoc inspections in accordance with [153].

Visits and *initial inspections* are made under agreements of the [153] and [66] type respectively, to verify the facility design information submitted by the State.

The majority of the inspection effort is expended on *routine inspections* [66/para.49 and 153/para.72]. The purpose of these is to verify that the information contained in reports submitted by the State is consistent with the accounting and operating records kept by the facility operator, to verify the location, identity, quantity and composition of safeguarded materials, and to verify information about the causes of shipper/receiver differences, book inventory uncertainties, and MUF.

Ad hoc inspections are made to verify the initial report or changes in the situation since the initial report was made, and to identify and verify the nuclear material involved in international transfers [153/para.71].

Under [153]-type agreements, *special inspections* are made under [153] in addition to routine inspections to verify information presented in special reports or to collect additional information when the IAEA considers the information provided by the State or obtained through routine inspections to be inadequate for it to fulfil its responsibilities. Document [66] authorizes the IAEA to carry out a special inspection if the study of a report indicates that such an inspection is desirable or if any unforeseen circumstances require immediate action.

Activities carried out by the IAEA during inspections and in connection with them are described in more detail in Section 2.4.

The safeguards agreement contains provisions for determining the frequency of routine inspections [66], or the maximum inspection effort [153]. A fraction of routine inspections may be of an unannounced character. Document [66] determines the maximum frequency of routine inspections (without specifying the duration of the individual inspections). The limit depends on whichever is the largest of: the inventory, annual throughput, or potential annual production of special fissionable material of the facility. This largest quantity (E) is measured in effective kilograms (e). For reactors and R&D facilities there are no routine inspections if E is less than 1 e and one routine inspection per year when E is between 1 e and 5 e; the inspection frequency above that point runs from two up to a maximum of twelve per year at 60 e. Beyond 60 e the right of access to the facility at all times is provided. In the case of reprocessing, conversion and fuel fabrication plants, two routine inspections per year are specified as long as E is 5 e or less. Above 5 e access at all times is foreseen.

For reactor and R&D facilities the actual frequency takes account of whether or not a reprocessing plant exists in the State, the nature of the reactors involved, and the nature and amount of nuclear material produced, used, stored or handled. For reprocessing plants, document [66] contains no special guidelines on the actual frequency of routine inspections. The type, isotopic composition and amount of safeguarded nuclear material in conversion plants and fabrication plants have to be taken into account in determining the actual frequency of routine inspections in those types of facilities. It is also important that the number, duration and intensity of inspections actually carried out shall be kept to the minimum consistent with effective safeguards implementation. For inspection planning purposes, the inspection frequency needed to implement [66]-type agreements is estimated and converted into man-days of inspection per year (MDI/a).

Paragraphs 79 and 80 of document [153] specify the maximum routine inspection effort (MRIE) measured in units of MDI/a[11]. For all types of nuclear installations with E less than 5 e, the limit is one routine inspection per year. For other facilities the inspection regime shall be no more intensive than is necessary but shall be sufficient to maintain continuity of knowledge of the flow and inventory of nuclear material. For reactors and sealed stores the limit is 50 MDI/a. In the case of facilities containing plutonium and uranium enriched to more than 5%, the equation $\text{MRIE} = 30\sqrt{E}$ MDI/a applies, but the MRIE should not be less than 450 MDI/a. For all other cases an MRIE equal to $(100 + 0.4E)$ MDI/a is specified. The total MRIE amounted to about 43 000 MDI/a for the nuclear activities covered by IAEA safeguards in 1982.

Paragraph 78 of [153] requires that the number, intensity, duration and timing of routine inspections be kept to a minimum consistent with the effective implementation of safeguards. As a result, an actual routine inspection effort (ARIE) is agreed in negotiations with States and stipulated in facility attachments. (The total agreed ARIE came to about one fourth of the MRIE for the nuclear activities covered by safeguards in 1982.)

In accordance with paragraph 81 of [153], due consideration should be given to the following when the ARIE and other elements of routine inspection of any facility are being established:

(a) the form and accessibility of the nuclear material
(b) the effectiveness of the SSAC and the extent to which the operator is functionally independent of the SSAC
(c) the characteristics of the State's nuclear fuel cycle, in particular the number and types of facilities and the characteristics of such facilities relevant to safeguards

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[11] The stipulation of inspection effort in units of MDI/a as defined by [153/para.109] is somewhat ambiguous: one MDI may mean a very short access to the facility for removal and reloading of the film from a camera system, or continuous inspection for a period of eight hours. Therefore, comparisons between figures for different facilities may be misleading.

(d) the international interdependence of nuclear activities involved and any relevant IAEA verification activities
(e) technical developments in the field of safeguards.

Points (a), (b) and (c) have usually been taken into account in establishing the ARIE figures and determining the inspection procedures for various types of facilities and for individual facilities[12]. Point (d) is used in reconciling inventory change reports from different States. Aspect (e) is generally reflected in Facility Attachments; since technical developments are constantly taking place, this point is relevant in negotiating new Facility Attachments and updating existing ones.

That part of point (c) which concerns the State's nuclear fuel cycle (in particular the number and types of facilities) is related to the question of economy of resources. Guidance on this question is provided mainly in paragraph 6(c) of [153], which suggests verification procedures be concentrated on those stages of the fuel cycle which involve the production, processing, use or storage of nuclear material from which nuclear explosives could readily be made, i.e. HEU and plutonium. Therefore, the verification effort is concentrated on spent fuel in the case of power reactors operating with natural uranium or LEU, on fresh fuel in the case of power reactors fuelled with plutonium or HEU, and on HEU and plutonium in the case of research reactors, critical assemblies and bulk handling facilities. Studies were started in 1983 on the wider interpretation of point (c). These and other considerations might result in different inspection efforts at a given type of facility in different countries depending on the characteristics of the respective fuel cycles.

2.4. INSPECTION ACTIVITIES

The activities of IAEA inspectors during and in connection with a visit to or inspection of a nuclear facility have been described in general terms in Section 2.3. Such activities depend to a certain extent on the particular situation (type of agreement and facility, number of inspections per year, etc.). Certain of these activities, however, have common features independent of the specific circumstances. In order to avoid repetition in the subsequent discussion of safeguards approaches for various facility types, a brief description of characteristic activities is first given here.

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[12] Point (b) is taken into account explicitly in safeguards agreements which include special arrangements for co-operation between the IAEA and the SSAC (Euratom and Japan). In these cases the IAEA's ARIE may be lower than in the standard case. For Euratom, the timeliness requirements for reports are longer than in the standard case.

Safeguards implementation starts at a facility coming under safeguards with an initial visit [153] or initial inspection [66] by IAEA inspectors. The purpose of these is to verify the accuracy and completeness of the design information on the facility which the State has to submit to the IAEA as early as possible before nuclear material is first introduced. This information (describing the facility and in particular its design features, operation modes and procedures relevant to safeguards) is examined by the IAEA prior to the initial visit for the purpose of developing an appropriate safeguards approach (Section 3.1). The initial visit is also used to consider the conclusions of the design examination, to collect any necessary additional information and to prepare the Subsidiary Arrangements.

2.4.1. Routine inspections

As stated in Section 1.3, IAEA verification essentially means testing diversion hypotheses. The purpose of the following activities, performed during or in connection with routine inspections, is to carry out such tests. Each of these activities has the potential to disclose one or more anomalies corresponding to specific elements in the diversion hypotheses. If any anomaly is found, its cause has to be ascertained immediately.

In the following list, the nature of each activity, i.e. whether it is related to NMA or C/S, is indicated in parentheses.

I.1. Follow-up actions (NMA and C/S)

Individual inspections are not usually independent of each other. It may be necessary to complete actions which were started during the previous inspection(s) and to resolve problems which have been identified in the meantime.

I.2. Accounting records examination (NMA)

The purpose of this activity is to establish for the MBA by independent audit a correct set of data upon which physical verification can be based. It should also enable an assessment to be made of the quality of the operator's system of accounting records. The examination is carried out with respect to the completeness, internal consistency and arithmetic correctness of the data and includes the checking of supporting documents and, if relevant, confirmation from operating records.

Finally the book inventory totals are checked and – in the case of PIT – the physical inventory totals are recorded. The examination is usually carried out in connection with one or more of the NMA activities I.3–I.8.

I.3. Operating records examination (NMA)

A correct set of facility operating data is in many cases necessary for comparison with accounting records or for deriving additional data or conclusions. The operating records include:

- operating data used to establish changes in the quantity, composition and location of nuclear material
- data obtained from calibration, sampling and analyses
- information on procedures for controlling the quality of measurements, and on the evaluation of the results
- information on the preparation for a physical inventory taking
- information relating to the cause and magnitude of any accidental or unmeasured loss.

The examination is also used as an opportunity to assess the quality of the operator's system of operating records and to offer advice if requested.

I.4. Reconciliation of accounting and operating records (NMA)

The purpose of the reconciliation is to identify and clarify any inconsistency between the accounting and operating data. Examples might be the comparison of recorded fuel assembly movements or loading patterns with accounting entries, or the analysis of a reactor operating history (operation time, power output) in relation to nuclear material production and nuclear loss.

I.5. Comparison of records and reports (NMA)

This activity consists in making a correlation between the relevant facility accounting and operating records on the one hand, and the State reports (ICR, MBR, PIL) on the other in order to determine their completeness, internal consistency and arithmetic correctness.

I.6. Updating of the book inventory (NMA)

An important step in NMA consists in establishing the amount of nuclear material that should be present at the facility – the book inventory at the date or near the date of inspection. The updating is based on the book inventory established at the previous inspection and uses facility records and supporting documents covering the intervening period. At times of physical inventory verification (PIV) the relevant book inventory may be used for the preparation of preliminary sampling plans.

I.7. Inventory change (flow) verification (NMA)

This activity involves verification of important components of the material balance, namely:

Increases:	such as imports from abroad, domestic receipt, nuclear production, de-exemption, etc.
Decreases:	such as exports, domestic shipment, nuclear loss, transfer to retained waste, exemption, etc.

In addition to the document audits under I.3–I.6, the following activities may be carried out:

- removal of seals and/or verification of receipts
- verification and sealing of shipments (e.g. partially filled irradiated fuel assembly casks)
- verification at other MBAs of matching receipts/shipments
- verification of shipper/receiver differences
- calculations for assessing nuclear loss and production (also in connection with physical inventory verification).

I.8. Inventory verification (NMA)

The inventory verification is carried out to confirm the operator's recorded book inventory of nuclear material present at a given time within an MBA. There are two types of inventory verification: the PIV which follows closely on or coincides with the PIT by the operator and closes the material balance period; and the interim inventory verification, which does not coincide with the closing of a material balance period and during which part or all of the inventory is verified. An interim verification is made if only part of the inventory is accessible or if the action is required in order to attain IAEA timeliness goals.

The basis for a PIV is an itemized inventory list prepared by the operator and organized by location (KMP) and material type, or some such equivalent documentation. In the case of items, the PIV is carried out by item counting, item identification and 'attribute tests' (NDA applied to a random sample of the items in order to detect dummies or other anomalies if present). For bulk material, 'variables tests' are made in addition to the above activities in order to determine the amount and isotopic composition of the material present (e.g. weighing, radiation measurement or chemical analysis of random samples). The verification results are compared with the physical inventory listings submitted by the State.

I.9. Verification at special strategic points (various measures)

The list of verification activities I.2–I.8 is not exhaustive. One example of a different category is the special arrangement foreseen for the cascade hall of enrichment plants (see Section 3.11). Another example would be reprocessing plants. Here, special SPs define the access to the various instrument readings and measurements or calibrations which are used by the operator to identify nuclear material or to provide information on the quantity, quality and location of nuclear material.

I.10. Application and use of surveillance (C/S)

Surveillance is used to detect possible movements of nuclear material, production of special fissionable material which contrary to agreed procedures has not been recorded or reported, falsification of information on the location, composition and quantity of nuclear material, unreported changes of the facility design, or any tampering with containment or IAEA safeguards devices. Automatic film cameras and closed-circuit TV systems are the most frequently used types of ASVS.

The installation of an ASVS requires careful analysis of the location (in the containment, along routine paths followed by nuclear material, etc.) and proper positioning. During maintenance, the integrity of the containment (signs of modification) and of the ASVS (indications of interference) are checked. The characteristics of the system may be such that the frequency of maintenance (change of films, batteries, tapes, etc.) coincides with timeliness requirements, so that maintenance can be carried out when surveillance records have to be evaluated. The evaluation of exposed films (video tapes) involves checking on significant events, e.g. number of appearances or disappearances of spent fuel casks, and their correlation with the operator's accounting and reporting records.

I.11. Application and use of seals (C/S)

Seals are tamper-indicating devices used to join movable segments of a containment structure in such a manner that access to a sealed item becomes impossible without opening of the seal or other obvious interference with containment integrity. Seals are used, for example, at the following locations:

- shields covering reactors
- channel gates, doors and other access possibilities
- fresh fuel racks, stacks of spent fuel, fuel assemblies
- spent fuel casks and other containers
- valves, levers, instruments

- IAEA equipment and other items (samples, standards, documents) stored at the facility.

Seals have to be verified at specified intervals on the spot. The intervals are usually related to the timeliness requirements. Additionally, samples of the most commonly used metal seals are checked at IAEA Headquarters. All data related to seals are recorded. Under certain conditions (ageing of seals, doubts as to the integrity of seals or containment), follow-up actions may include remeasurement of the nuclear material involved.

Radiation monitors are used in a manner similar to seals: they indicate for example whether or not spent fuel has passed an access port or a containment penetration.

I.12. Verification of adequacy of the operator's measurement system

According to paragraph 81 of [153], the extent to which an SSAC has fulfilled the various requirements of paragraph 32 of that document has to be taken into account in the determination of the ARIE. In this context, verification of the functioning and calibration of relevant instruments is necessary, together with an evaluation of the precision and accuracy of the operator's measurements in relation to international standards.

I.13. Other inspection activities

The list of typical inspection activities I.1–I.12 is not exhaustive. Special technical or legal situations may require other kinds of activity. Furthermore, IAEA safeguards approaches are still evolving and new developments may lead to changes in implementation practice.

2.5. SAFEGUARDS EFFECTIVENESS

Paradoxically, effective safeguards contribute to the impossibility of measuring safeguards effectiveness by means of the simplest indicator, i.e. the percentage of diversion acts detected during a given year. Under these circumstances the only way of making the credibility of safeguards apparent is to carry out periodic and critical reviews of verification activities. This is done by means of annual reports to the Board of Governors of the IAEA. However, there is no method yet available to define safeguards effectiveness in a well-characterized quantitative manner. Other indicators related to effectiveness must therefore be analysed. Two factors are particularly relevant:

- the extent of safeguards implementation achieved: this can be defined as the percentage of nuclear material/facilities under safeguards for which the inspection goals have been fully attained, and

- the level of assurance attained: this depends on, among other things, the overall probability of detection of a diversion.

The extent of implementation and level of assurance are the main factors to be considered in assessing the effectiveness of safeguards. While it is not too difficult to determine the first factor, the level of assurance cannot be directly derived from the degree of goal attainment. This is because the level of assurance, which is related to the detection probability, is only implicitly contained in the criteria used for the evaluation of goal attainment. It should be noted that these criteria have been applied more and more rigorously in evaluating safeguards effectiveness over the years as more manpower and equipment have become available and more systematic evaluation methods have been introduced.

In order to improve the effectiveness of safeguards, the IAEA endeavours to improve both of the two factors mentioned above, i.e. to increase the number of facilities in which the inspection goals are fully attained and to improve the overall detection probability.

In assessing the effectiveness, and thereby the credibility of IAEA safeguards, it should not be forgotten that Member States are not restricted to the conclusions and reports of the IAEA as a source of information. They may possess information about unsafeguarded nuclear activities; they may also take into account the internal and external stability of States and assess their political intentions and their technological capabilities.

3. SAFEGUARDS APPROACHES

This part of the booklet describes the essentials of the IAEA safeguards approach for various important nuclear facility types on the basis of the concepts and methodology explained in Sections 1 and 2 above. Nuclear facilities of a given type often vary considerably in their design and operating features which are relevant to safeguards and thus to the inspection effort required. In order to make this presentation reasonably precise, attention is focussed on typical cases and the description is simplified and schematized as far as possible. Any comparison between the outlines given below and actual safeguards implementation requires consideration of the special circumstances in each given case. The examples of inspection effort and reporting requirements correspond to standard [153]-type agreements[13].

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[13] See footnote 12 on page 16.

3.1. DESIGN OF THE SAFEGUARDS APPROACH

A safeguards approach is the system of NMA, C/S and other measures considered as necessary and sufficient to test the diversion assumptions identified by the diversion analysis in a given situation. Safeguards approaches are designed for generic types of nuclear facilities (model approaches) and, by modification of the model approaches, for individual facilities (facility approaches). The provisions necessary to implement the facility safeguards approach are incorporated in the Safeguards Agreement and, where applicable, in the Subsidiary Arrangements and the Facility Attachments. The design of safeguards approaches takes into account among other factors:

- the purposes, technical objectives, basic concepts and measures defined by [66] and [153] as outlined in Sections 1.1 to 1.4
- the terms of the relevant safeguards agreement and other basic documents
- the relevant design characteristics and operating practices of the facility under consideration, as reported by the State and verified by the IAEA
- the expected technical effectiveness of the SSAC or other relevant accounting and control systems (Section 1.5), in particular the effectiveness of the measurement system and the accuracy of measurements, the promptness of the States' reports and their consistency with results of IAEA verification activities
- the detection goals as described in [SGI/1] and [SGI/4]
- the technical limitations of safeguards measures (measurement accuracy achievable according to international standards, reliability of C/S equipment, etc.)
- diversion assumptions and concealment methods (Section 2.2).

As a result of system-analytic studies based on these factors, the following main components of the safeguards approach are identified:

- design and operations characteristics of the facility relevant to safeguards
- an MBA structure covering the facility and a set of SPs, in particular KMPs
- plausible diversion and concealment assumptions and the anomalies corresponding to these assumptions
- inspection goals reflecting the actual conditions at the facility and the given legal and technical constraints
- recording and reporting requirements
- special NMA features, such as requirements, procedures, and timing for verification of the quantity, composition, and location of nuclear material
- appropriate combinations of C/S measures and the SPs at which they are to be applied
- the number, duration, timing and mode of routine inspections, and
- the set of inspection activities to be carried out during routine inspections in a typical NMA cycle (inspection plan).

The safeguards approach for the main nuclear facility types will be now outlined in accordance with the above listing.

3.2. LIGHT WATER POWER REACTORS (LWRs)

3.2.1. Features of relevance to safeguards

Of all major types of nuclear facilities, the IAEA has accumulated most safeguards experience with light water power reactors (LWRs) (approximately 115 covered by safeguards). The LWR is a typical item facility and the flow of the large items (fuel assemblies) from the fresh fuel storage through the reactor to the spent fuel pond is quite easily observed. This facilitates application of NMA measures. Fuel assemblies, in the standard case containing low enriched uranium oxide, are manufactured to rigorous specifications at the fuel fabrication plant. This provides an opportunity to verify the amount and composition of the fresh fuel at this point of the fuel cycle. During the residence of the fuel in the power plant the composition changes in a way which can only be verified by NDA and assessed by calculation; however, this poses no problem as long as the integrity of the fuel assemblies is maintained[14]. The actual amount and composition of the nuclear material contained in spent fuel assemblies is determined later, outside the LWR, after dissolution of the assemblies in a reprocessing plant.

The design of most LWRs offers favourable conditions for the application of C/S measures. The reactor vessel constitutes a containment, the access to which can be monitored by a seal, for example at the missile shield. Seals are also applied to partially filled shipping containers of spent fuel. A spent fuel pond covered by automatic surveillance systems (ASVS) is another example of the application of C/S measures.

If the fresh fuel for an LWR contains only LEU, the spent fuel which contains plutonium is of higher strategic value and so a greater safeguards effort is devoted to it. In a typical LWR facility most of the plutonium produced is contained in the irradiated fuel stored in the spent fuel pond, with the remainder in the core. Removal of spent LWR fuel assemblies requires a large and heavy container which can be monitored by ASVS at the spent fuel pond.

A typical LWR runs on a twelve- to eighteen-month fuelling cycle. At the end of that period there is a shutdown for refuelling and maintenance; this

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[14] This can be established by the use of C/S measures. Additionally, in those cases where the welded design of the fuel assemblies makes disassembly difficult, the engraved serial number can be used for identification. Where fuel assemblies can easily be dismantled and the rods exchanged, item identification is not considered reliable and more detailed accounting procedures are applied.

lasts approximately six weeks. During each shutdown the reactor pressure vessel is opened and about one fifth to one third of the fuel is discharged and replaced. The remaining fuel is generally repositioned for the next operating cycle. In multi-unit plants, spent fuel may be transferred to central storage locations. This may require continuous inspection during the transfer.

Under [66]-type agreements it is not only the nuclear fuel but also the whole facility or specific items of equipment (reactor vessel, main circulation pump, etc.) that are usually subject to safeguards. In most instances normal operation of the plant is an indication that the items concerned have not been removed. Safeguarding the nuclear material also implies examining the hypothesis that the facility or its components are being misused.

3.2.2. Structure of MBA

Light water reactor facilities are usually considered as a single MBA including the following SPs:

Inventory KMPs – fresh fuel storage / reactor core / spent fuel pond

Flow KMPs – receipt of fresh fuel / shipment of spent fuel / 'rebatching' (if dismantling of fuel assemblies is possible) / nuclear loss (burnup) and plutonium production in the fuel

C/S-SPs – reactor hall and access routes to it (seals, ASVS) / spent fuel pond (seals, ASVS).

A similar structure is used in the case of plants incorporating more than one reactor unit with an inventory KMP for each core. In such plants, simultaneous PIV or particularly careful C/S monitoring at all other units of the plant is required to exclude the possibility of concealment by temporary 'borrowing' of fuel assemblies.

3.2.3. Diversion assumptions

Table I shows simplified examples for LWRs of diversion paths and concealment methods, the corresponding anomalies, and the inspection activities[15] intended to reveal them (see Sections 2.4 and 2.5). Item identification is not applied if fuel assemblies can easily be dismantled.

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[15] In this and all subsequent sections, the activities described are those applied according to present practice and with existing equipment.

TABLE I. EXAMPLES OF DIVERSION ANALYSES FOR LWRs

Diversion	Concealment methods	Anomalies	Inspection activities[a]
This row applies to all the diversions listed below	Falsification of documents	Inconsistencies in documents	NMA I.2–I.8
1. Removal of fresh fuel assemblies from storage	Substitution with dummies	Incorrect composition and/or enrichment	NMA I.8 – NDA
	Substitution with borrowed fuel	Assemblies missing in another MBA	Simultaneous inspection
2. Removal of irradiated fuel assemblies from the core	Substitution with fresh fuel	C/S devices indicate anomaly	C/S I.10 – ASVS during reloading C/S I.11 – Sealing of reactor vessel
		Incorrect composition or irradiation status of fuel	NMA I.8 – NDA
3. Unreported irradiation of fertile material (Pu production)	Replacement of guide tube fillers with U-containing rods	Unreported shutdowns, presence of unreported material	as in case 2

4. Removal of spent fuel assemblies[b] from storage pond	Substitution with dummies	C/S devices indicate anomaly	C/S 1.10 – ASVS
		Incorrect composition or irradiation status of fuel	NMA 1.8 – NDA
	Substitution with borrowed fuel	Assemblies missing in another MBA	Simultaneous inspection
5. Removal of spent fuel from container (or during transit)	Substitution with dummies	Incorrect loading	C/S 1.11 – Observation of loading or verification plus sealing of partially filled container

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[a] See abbreviations on page 69.
[b] or of fuel rods after dismantling of assemblies.

TABLE II. EXAMPLE OF A SIMPLIFIED ANNUAL INSPECTION PLAN FOR AN LWR

Inspection	Purpose/Reason	*MDI*[a]	*Inspection activity*[b]
1	Starting of PIV	1	I.10, I.11
2	PIV (fresh fuel, core, spent fuel)	5–8	I.1–I.11
3	Closing of PIV	1–2	I.10, I.11
4–6	Interim inspection: ASVS maintenance (coincides with timeliness requirements for spent fuel); remaining NMA activties	4–6	I.1–I.6, I.8, I.10, I.11[c]
(i)	Loading of spent fuel containers	1–2[d]	I.7, I.10, I.11
(ii)	Re-establishing of inventory	2–3[d]	I.8

[a] An MDI means access by the inspector to the facility for a time period ranging from a short visit up to 8 hours work per calendar day (see Section 2.3). See also footnote 12 on page 16.

[b] See abbreviations on page 69.

[c] As appropriate.

[d] Per event.

3.2.4. *Inspection goals*

The main inspection goal is the capability of detecting the diversion of one SQ of nuclear material (this is usually more than the amount contained in one fuel assembly), including special fissionable material which can be produced as a result of unreported irradiation, in accordance with the following timeliness guidelines:

- within 4 weeks for fresh MOX fuel;
- within 3 months for irradiated fuel; and
- within 12 months for fresh LEU fuel.

3.2.5. Recording and reporting requirements

- At the facility: for [153] and [66], accounting and operating records supported by source documents
- ICR: for [153], 30 days after the end of the month in which the inventory change occurred; the calculated plutonium content of the spent fuel should be reported as of the date of discharge from the reactor
- MBR and PIL: for [153], within 30 days after each PIT, usually after refuelling;
  for [66], accounting and operating reports two to twelve times a year as agreed.

3.2.6. Special NMA features

Application of standard NMA activities I.2–I.8 poses no special problem in the case of fresh fuel. Identification of spent fuel by means of the Cerenkov light emitted is a very effective technique. A PIT and PIV are conducted after refuelling and before the reactor vessel is closed.

3.2.7. C/S measures

- Sealing of the reactor biological or missile shield; if applicable, back-up by ASVS
- Application of one or more ASVS at the spent fuel pond
- Surveillance of the loading and/or sealing of spent fuel containers.

3.2.8. Routine inspection plan

Table II shows a typical inspection cycle at an LWR for a calendar year. If the operation of the plant is extended without refuelling beyond one year, a partial inventory verification covering the core is made after shutdown during one of the interim inspections. The table indicates the inspection activities identified by the code used in Section 2.4 and provides an estimate of the inspection effort necessary in man-days of inspection work (MDI). In most cases the ARIE for an LEU-fuelled LWR under normal operating conditions is about 14–16 MDI/a. This compares with an MRIE of 50 MDI/a. Inspections (i) and (ii) are additional to those included in the ARIE and are as follows:

(i) Surveillance of the loading and/or sealing of spent fuel containers, in particular of partially filled containers;
(ii) Re-establishment of the inventory after loss of continuity of surveillance.

3.3. RESEARCH REACTORS

Most of the 150 research reactors under safeguards are of the swimming pool type and the following discussion is restricted to those. Much of what has been said in Section 3.2 basically applies also to swimming pool research reactors, although they present a far simpler and more self-evident safeguards situation.

The fuel assemblies of many of the swimming pool reactors contain HEU, although only in small quantities (less than 2% SQ). The remaining assemblies usually contain LEU or a mixture of LEU and HEU. The core is normally visible and accessible for measurements; the number of fuel assemblies at the facility is rather small and the total amount of nuclear material on inventory is usually below one SQ.

In most cases the power of research reactors is limited to less than 1 MW(th) and the only plausible diversion hypothesis is the removal of (preferably fresh) fuel assemblies. Falsification of documents and replacement of removed fuel by dummies could be used for concealment. But even if all the fuel were diverted, which could easily be detected, less than one SQ could be obtained in one year. Under these conditions one inspection per year (1–3 MDI) is deemed sufficient. A typical inspection consists of a records audit (I.2–I.7) and PIV (item counting, item identification and exclusion by NDA of material substitution). The inspection goals for research reactors are usually the same as for LWRs. The accuracy of item counting at research reactors is one fuel assembly, usually containing far less than one SQ.

Some research reactors operate at higher thermal power or contain one SQ or more of nuclear material (or both). In this case the diversion hypothesis has to include not only the diversion of fuel but also the unreported production of plutonium by irradiation of fertile material within or around the core. Both cases can be covered by more frequent inspections and C/S measures. However, they must be analysed separately to determine the actual conversion potential of the reactor and the appropriate safeguards measures required. The safeguards approach is based on the fact that for the production of plutonium large amounts of fertile material have to be put into the reactor and, after irradiation, have to be removed from it. Unreported production of plutonium can be detected by monitoring by ASVS the number of item transfers to and from the reactor core (many hundreds per year as against a few dozens for normal operation). Timeliness considerations may require up to twelve inspections per year for film evaluation (1 MDI each). Some of these will be used for NMA measures (1–3 MDI each).

3.4. CRITICAL ASSEMBLIES

3.4.1. Features of relevance to safeguards

Critical (and subcritical) assemblies play an important role in reactor research. About 25 such facilities are under IAEA safeguards. In contrast to research reactors, they have no provision for heat removal and only limited radiation shielding. The cores of critical assemblies are designed for fuel arrangement flexibility and use fuel in readily accessible form for studies of various reactor lattice configurations.

One type of critical assembly uses fuel platelets or pins enclosed in a metallic cladding and assembled in drawers. The core is made up of arrays of such drawers. In this case the platelets or pins are considered as accounting items. Another type uses fuel rods consisting of sealed metallic cans filled with fuel pellets. The rods are packed into fuel assemblies and the core is composed of such assemblies. In this case the rods are usually considered as accounting items.

The composition of the items in a critical assembly is well known and it remains practically unchanged because the burnup is negligible. The items can be handled and measured safely. The total fuel inventory is generally static, with only limited shipping and receiving activities. On the other hand, the experimental programme requires many changes of the core configuration and thereby many movements of a large number of items[16]. This creates the main safeguards problems with critical assemblies and in particular with those few of major safeguards interest which contain hundreds of SQs of HEU or plutonium in the form of metal or oxide. These are amongst the most sensitive facilities in a State.

Large critical assemblies usually consist of a reactor hall, a main storage facility containing the fuel not being used in the core, and an assembly area

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[16] This number ranges from several tens to hundreds of thousands.

TABLE III. EXAMPLES OF DIVERSION ANALYSES FOR CRITICAL ASSEMBLIES

Diversion	Concealment methods	Anomalies	Inspection activities[a]
1. Removal of fuel from the core	Falsification of documents	Inconsistencies in documents	NMA I.2–I.8
	Misrepresentation of the material	Incorrect core structure	NMA I.8 – NDA; physical measurements
	Substitution with dummies	Incorrect composition and/or enrichment	NMA I.8 – NDA; physical measurements
	Borrowing of fuel, e.g. from assembly room	Fuel missing in the assembly room	NMA I.8; simultaneous inspection C/S I.10 – ASVS C/S I.11 – Sealing
2. Removal of fuel from the storage or assembly room	Falsification of documents	Inconsistencies in documents	NMA I.1–I.8
	Substitution with dummies	Incorrect composition and/or enrichment	NMA I.8 – NDA
	Borrowing of fuel from the core	Fuel missing in the core	NMA I.8; simultaneous inspection C/S I.10 – ASVS C/S I.11 – Sealing

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[a] See abbreviations on page 69.

connecting the storage facility and the reactor. Drawers or assemblies are prepared and reshuffled in the assembling area. For safety reasons, access to these rooms is restricted and fuel can be removed only through a few penetrations. These can be covered by C/S measures. Of particular interest for safeguards purposes are door monitors used by the operator for access control (persons and nuclear material) provided that their operation is verifiable[17] and the conditions for containment integrity are met. In order to freeze as many of the large number of items as possible, seals are applied as far as permitted by the operation of the critical assembly, e.g. at fuel containers in the storage room, at drawers, assemblies, etc.

3.4.2. Structure of MBA

Critical assemblies are usually considered to be a single MBA including:

Inventory KMPs – storage rooms / reactor room / assembly area

Flow KMPs – receipt of fuel / shipment of fuel

C/S-SPs – core, or parts of the core, if applicable (seals) / storage cells, storage cassettes, bird cages, drawers, assemblies (seals) / assembly area (ASVS) / access routes to the storage (ASVS, seals) / access routes to the core (ASVS, seals).

3.4.3. Diversion assumptions

Table III shows simplified examples of diversion paths and concealment methods, the corresponding anomalies, and the inspection activities intended to reveal them (see Sections 2.4 and 2.5).

3.4.4. Inspection goals

The inspection goal is the capability of detecting the diversion of one SQ of nuclear material. One SQ may range from some hundreds (plutonium) to several thousand (natural uranium) items. Timeliness guidelines:

- within 4 weeks for plutonium and HEU; and
- within 12 months for natural uranium and LEU.

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[17] Means for verification are still under development.

TABLE IV. EXAMPLE OF A SIMPLIFIED ANNUAL INSPECTION PLAN FOR A CRITICAL ASSEMBLY

Inspection	Purpose/Reason	MDI	Inspection activity[a]
1–2	PIV (core and storage)	20–40	I.1–I.10
3–24	Interim inspection activities at SPs: NMA – NDA; seals	150–240	I.1–I.11
(i)	Re-establishing inventory	10[b]	I.8, I.10, I.11

[a] See abbreviations on page 69.

[b] *Per event.*

3.4.5. Recording and reporting requirements

- At the facility: for [153] and [66], accounting and operating records supported by source documents
- ICR: for [153], 30 days after the end of the month in which the inventory change occurred
- MBR and PIL: for [153], within 30 days after each PIT, usually once to twice a year;
  for [66], accounting and operating reports 2–12 times a year as agreed.

3.4.6. Special NMA features

The large number of items require application of sampling techniques. Sealing and other C/S measures are used during PIV in order to prevent the same items from being presented twice for counting.

3.4.7. C/S measures

- Sealing of storage rooms, cells, cassettes, bird cages
- Application of ASVS, and seals, at access routes.

3.4.8. Routine inspection plan

Table IV shows a typical inspection cycle for a calendar year at a critical assembly containing large amounts of plutonium or HEU. The total ARIE for large critical assemblies varies from about 170 to 280 MDI/a (continuous inspection). This compares with an MRIE of about 600 MDI/a. Inspection type (i) represents an additional effort, not included in the ARIE, for re-establishment of the inventory after loss of continuity of surveillance.

3.5. ON-LOAD FUELLED POWER REACTORS

3.5.1. Features of relevance to safeguards

About 30 power reactors presently under safeguards are refuelled continuously, without reactor shutdown, by means of remotely controlled charge-discharge machines. The variety of these on-load fuelled reactors is considerable, CANDU and Magnox types being the most frequent. The following discussion is based on a large, single-unit CANDU plant as an example but reference is also made to multi-unit power plants.

Most of the on-load fuelled reactors under IAEA safeguards use natural uranium; the fuel bundles are usually much smaller than LWR fuel assemblies and the annual throughput of items is, for comparable power, much larger. The composition of the fuel and its transformation as a result of burnup in the reactor have been described in the first paragraph of Section 3.2. The plutonium produced in the fuel bundles is of higher safeguards relevance than the uranium in the fresh fuel. For this reason the safeguards approach for on-load fuelled reactors concentrates on spent fuel.

In contrast to LWRs, the core is practically inaccessible and the reactor vessel cannot be considered as a sealable containment. As a consequence, the fuel in the core, which constitutes a substantial component of the nuclear material inventory of the plant, cannot be verified routinely by NMA or by seals examination. The route of the fuel bundles through the plant is complicated and only to a certain extent accessible. This is particularly true of the spent fuel. Furthermore, the fuel bundles are small compared to LWR assemblies and so many possibilities exist for their removal over undeclared routes. These plant features require extensive use of C/S measures. This applies in particular to non-full-scope safeguards situations, where verification of the fresh fuel at the fabrication plants supplying the reactor and at the reprocessing plants receiving the spent fuel is impossible because these facilities are not covered by a safeguards agreement.

With respect to spent fuel, the safeguards approach aims at verifying the flow leaving the reactor by means of an automatic bundle counter and at maintaining the continuity of the resulting data by monitoring the flow of bundles between the reactor and the storage pond through the use of extensive C/S measures. For this purpose a complex network of closed-circuit television cameras connected to a central recording station has been developed and put into operation at certain plants. In the case of multi-unit plants, fresh-fuel bundle counters are also used.

The design features of the spent fuel storage pond are not basically different from those at LWRs; however, the large number of bundles accumulating in the pond makes PIV more difficult. The verification can be facilitated by storing whole stacks of fuel bundles in sealable form, e.g. in large baskets. In some cases, spent fuel may be transferred in batches to intermediate storages or shipped to reprocessing plants. This may require continuous inspection during the transfer or loading.

On-load fuelled reactors present a veriety of specific technical features which require special safeguards approaches. Some of these reactors contain, for example, MOX fuel or HEU booster rods. It is not possible to discuss the details in a condensed presentation such as this.

3.5.2. Structure of MBA

On-load fuelled reactor facilities are usually considered as a single MBA including the following SPs:

Inventory KMPs – fresh fuel storage room / fresh fuel loading room, transfer mechanisms and fuelling machines[18], reactor[18], including control room / spent fuel discharge room, discharge machine[18] and transfer canal / spent fuel reception bay / spent fuel storage bay

Flow KMPs – receipt of fresh fuel / nuclear loss (burnup) and plutonium production in the fuel / shipment of spent fuel

C/S-SPs – fresh fuel storage (ASVS) / fresh fuel loading port (fresh fuel bundle counter[19]) / locations inside the reactor containment and access routes (seals, ASVS, radiation monitors) / spent fuel discharge ports (spent fuel bundle counter) / spent fuel reception bay (ASVS) / spent fuel storage bay (ASVS, seals).

If this structure is also used in the case of plants equipped with more than one reactor unit, simultaneous PIVs or particularly careful C/S monitoring at all units of the plant during the PIV is required to exclude the possibility of concealment of diversion by the 'borrowing' of fuel bundles.

3.5.3. Diversion assumptions

Table V shows for the case of a typical on-load fuelled reactor simplified examples of diversion paths and concealment methods, the corresponding anomalies, and the inspection activities intended to reveal them (see Sections 2.2 and 2.4).

3.5.4. Inspection goals

The main inspection goal is the capability of detecting the diversion of one SQ of nuclear material (e.g. about 150 irradiated natural uranium fuel bundles), including special fissionable material which can be produced as a

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[18] The reactor, and the fuelling and discharge machines are routinely inaccessible for PIV. The KMPs formally serve for the calculation of the core inventory on the basis of input and output flows.

[19] In the case of multi-unit plants.

TABLE V. EXAMPLES OF DIVERSION ANALYSES FOR ON-LOAD FUELLED REACTORS

Diversion	Concealment methods	Anomalies	Inspection activities[a]
This row refers to all the diversions listed below	Falsification of documents	Inconsistencies in documents	NMA I.2–I.8
	Tampering with IAEA equipment	Traces of tampering	C/S I.11 – Sealing
1. Removal of fresh fuel bundles from storage	Boxes partially filled or incorrectly stacked	Incorrect number of boxes or fuel bundles	NMA I.8
	Substitution with dummies	Bundles contain no fuel or depleted fuel	NMA I.8 – NDA
	Substitution with borrowed fuel bundles	Bundles missing in another MBA	Simultaneous inspection
2. Removal of irradiated fuel bundles from the core or from discharge machine	Use of irregular fuel paths	C/S devices indicate anomaly	C/S I.10 – ASVS in charge and discharge room; ASVS, seals and radiation monitor at access routes; NMA I.7 – bundle counter
3. Unreported irradiation of fertile material (production of Pu)	Use of irregular fuel paths	C/S devices indicate anomaly	as in case 2
		Unreported design changes	as in case 2
4. Removal of spent fuel bundles from regular paths after leaving discharge port	Use of irregular fuel paths	C/S devices indicate anomaly	C/S I.10 – ASVS covering fuel paths

5. Removal of spent fuel bundles from storage pond	Substitution with dummies	C/S devices indicate anomaly	C/S I.11 – ASVS
		Incorrect composition or irradiation status of fuel	NMA I.8 – NDA
	Substitution with borrowed fuel bundles	Bundles missing in another MBA	Simultaneous inspection
6. Removal of spent fuel from container (also in transit)	Substitution with dummies	Incorrect loading	C/S I.11 – Observation of loading; verification and sealing of shipping container

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[a] See abbreviations on page 69.

result of unreported irradiation, in accordance with the following timeliness guidelines:

- within 4 weeks for fresh MOX fuel or HEU;
- within 3 months for irradiated fuel; and
- within 12 months for fresh natural uranium or LEU fuel.

3.5.5. Recording and reporting requirements

- At the facility: for [153] and [66], accounting and operating records supported by source documents; reactor power history, loading patterns, and fuel flow through the core are of particular interest
- ICR: for [153], 30 days after the end of the month in which the inventory change occurred; the plutonium content of the spent fuel discharged should be reported monthly
- PIL and MBR: for [153], within 30 days after each PIT, usually once a year;
  for [66], accounting and operating reports 2–12 times a year as agreed.

3.5.6. Special NMA features

Verification of the fresh fuel inventory is carried out annually by opening fuel boxes at random as far as practicable. In the case of multi-unit plants, fresh fuel bundle counters are also applied.

The inaccessibility of the fuel in the core requires the following assumption to be made: after initial inventory taking, input to the core is considered equal to output as long as operating data and C/S do not indicate any anomaly. Verification of the spent fuel takes place after the book inventory of the fuel storage bay has been established by comparing the bundle counter reading with the inventory changes in the storage bay. The bundle counter also has an NDA function to verify the attributes of spent fuel bundles passing through.

If the heavy water at the facility is subject to safeguards, inspectors verify the operator's reading of instruments for heavy water flow or inventory and assess whether the calculation of the inventory and the losses claimed are reasonable. The stock is independently verified by weighing drums and taking samples on a random basis.

3.5.7. C/S measures

- ASVS in fresh fuel loading area, fuelling and discharge machine rooms, spent fuel receiving bay, defective fuel bay, and main storage pond

- Sealing of access routes to the reactor hall or placement of radiation monitors
- Sealing of spent fuel storage baskets.

3.5.8. Routine inspection plan

Table VI shows a typical inspection cycle at an on-load fuelled reactor for a calendar year. The total ARIE under normal operating conditions[20] is approximately 30–40 MDI/a for small reactors (below 200 MW(e)) and about 40–50 MDI/a for the example considered here (600 MW(e))[21]. This compares with an MRIE of 50 MDI/a. Lines (i) and (ii) indicate additional inspections as follows:

(i) Transfer of spent fuel to intermediate storages or reprocessing plants. The effort necessary for this activity may be considerable until C/S measures to cover transfers and sealable baskets for spent fuel stacks are available.

(ii) Re-establishment of the inventory after loss of continuity of surveillance.

3.6. FAST BREEDER REACTORS

IAEA experience is limited at present to experimental and prototype fast breeder reactors cooled by liquid metal (LMFBR). In the foreseeable future only fast breeder plants using this technology will come under IAEA safeguards; however, the design of the safeguards approach for large commercial LMFBRs will require more than simple extrapolation from the present experience. This discussion will therefore be limited to the salient features.

Liquid metal cooled fast breeder reactors are typical item facilities; the fuel assemblies are bulky and the number present at the plant is moderate. The main difference from typical LWRs and on-load fuelled reactors is the large inventory of plutonium and, in some cases, also of HEU, in the unirradiated fuel. In addition, as a result of the conversion of material of lower safeguards interest (natural or depleted uranium), breeders produce a surplus of plutonium, which is more suitable for explosive purposes than that normally produced in LWRs. Diversion of fresh fuel would be particularly attractive because of its content of direct-use material, its easy accessibility and the minimal radiation hazard.

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[20] Spent fuel transfers to an intermediate storage not included.

[21] The ARIEs given for the 600 MW(e) plant include MDIs required for maintenance of the complex C/S system.

TABLE VI. EXAMPLE OF A SIMPLIFIED ANNUAL INSPECTION PLAN FOR AN ON-LOAD FUELLED REACTOR

Inspection	Purpose/Reason	MDI	Inspection activity[a]
1	PIV (fresh fuel and spent fuel directly, core indirectly)	4	I.1–I.11
2–12	Interim inspection: ASVS maintenance (coincides with timeliness requirements for spent fuel); remaining NMA activities	44[b]	I.1–I.11
(i)	Transfer or shipment of spent fuel	as required	I.7, I.10. I.11
(ii)	Re-establishing inventory	up to 30	I.8

[a] See abbreviations on page 69.

[b] Depends on instrumentation available. Advanced equipment if operating reliably may permit lower effort; more effort may be necessary with standard equipment and if films or tapes cannot be removed from the facility.

As in the case of on-load fuelled reactors, the main feature of safeguards relevance of LMFBRs is the inaccessibility of the reactor core for verification purposes. Moreover, the route of the fuel from the reactor core to the irradiated fuel storage is also inaccessible: the assemblies are remotely handled and even in the storage either remain submerged in sodium for a long period of time, or are – after cleaning and drying – enclosed in cans to be stored in a water pond or gas cooled storage. Before canning, item identification by serial number may be possible.

The safeguards approach for the LMFBR is based on an item accounting system for fuel assemblies, complemented by extensive use of C/S measures.

Normally fresh fuel assemblies are verified carefully at the fuel fabrication plant and transferred to the power plant under seal. Direct item counting, identification and NDA measurements of fresh fuel assemblies are performed at locations within the accessible nuclear fuel handling area. For the inaccessible area, safeguards involves verifying the input and output flow of nuclear material in conjunction with the application of adequate C/S measures. Checking of operating records (charge-discharge operation, loading patterns) is also of relevance in this case. Before shipment, irradiated fuel and blanket assemblies are verified visually and/or by NDA on a random basis, placed into the shipping container and sealed. The timeliness goals (within 4 weeks) indicate the need for a higher frequency of inspection of fresh fuel than of irradiated fuel. However, some inspections for inventory verification of fresh fuel may be partially coupled with scheduled shipments of irradiated fuel from the reactor.

Many of the concepts relating to LWRs, and in particular on-load fuelled reactors (MBA structure, inspection goals, diversion analysis, etc.), will be incorporated into the design of a safeguards approach for large commercial LMFBRs. However, the necessary annual inspection effort may be considerable owing to the complexity of the plant and the many SQs of direct-use material involved.

3.7. STORAGE FACILITIES

Nuclear facilities usually include storages for nuclear material, e.g. fresh fuel storages or spent fuel ponds. There are, however, about 30 separate storage facilities under safeguards, containing source material, fresh or spent fuel assemblies, or separated plutonium. The safeguards approach for a separate storage – apart from its treatment as an individual MBA – is basically similar to that applied at the same type of storage incorporated in other types of nuclear facility. It is not therefore necessary to discuss such facilities separately.

Several States have started the construction of intermediate or long-term away-from-reactor storage facilities in order to deal with the accumulation of large numbers of spent fuel assemblies. These storages – being essentially enlarged reactor spent fuel ponds – again pose no fundamental problem to IAEA safeguards. However, certain peculiarities must be taken into account. The large numbers of fuel assemblies present mean that special procedures are required for PIT and PIV. In order to preserve continuity of knowledge, the IAEA will have to apply extensive C/S measures. Sealable baskets or racks containing stacks of fuel assemblies could be helpful in this respect.

Another alternative, the so-called 'dry' away-from-reactor storage facility consisting of arrays of transport containers filled with spent fuel assemblies, is again without special problems. The containers will be sealed after verification and surveillance measures applied.

3.8. CONVERSION AND FUEL FABRICATION PLANTS – LEU

There are a few separate chemical conversion facilities under safeguards which are fed by natural uranium concentrate and produce uranium hexafluoride (UF_6) as feed for enrichment plants or natural uranium fuel fabrication plants. According to the terms of [153], the conversion occurs before the 'starting point' of safeguards, whereas the UF_6 becomes subject to safeguards as it leaves the plant. In this case IAEA verification is restricted to confirming the output as declared by the operator, and this is done by weighing and analysing random samples taken from product cylinders. Under [66]-type agreements, uranium concentrate can be subject to safeguards.

Further conversion of UF_6 or conversion of U_3O_8 (yellow cake) to UO_2 or metal is often an integral process step in fuel fabrication plants. Scrap recycling may also be carried out at the same site. Typical fuel fabrication plants which include both of these processes and manufacture fuel assemblies containing LEU, i.e. assemblies for LWRs, are discussed below. Safeguards approaches for this type of facility are also essentially valid for those which process natural or depleted uranium. In total, there are about 40 facilities under safeguards which fall into one or more of the categories mentioned.

3.8.1. Features of relevance to safeguards

In LEU fuel fabrication plants of the type considered here, solid UF_6 is received from an enrichment facility in large transport cylinders. It is then converted into UO_2. After analysis, the UO_2 powder is blended, milled, granulated and pressed into 'green' pellets. These are sintered, ground to dimensional tolerances and loaded into fuel rod tubes. The end plugs of the loaded tubes are hermetically sealed and the rods incorporated into finished fuel assemblies. Substantial quantities of recoverable scrap (solid and liquid) are generated in the UF_6 to UO_2 conversion process and the pellet fabrication.

Most of the nuclear material inventory present is usually contained in items such as UF_6 cylinders and finished fuel assemblies. However, from the point of view of safeguards, these plants are essentially bulk handling facilities. The inventory of bulk materials in the facility may be upwards of several hundred tonnes, and it occurs in a variety of forms such as solutions, powder, pellets, rejected material awaiting recycling, and scrap material in heterogeneous forms. The material is distributed over large process areas and there are many interrelated flows. Only limited handling precautions are required from the standpoint of toxicity and criticality. Therefore the material is more or less accessible at all stages of the process and at all times. Only the starting point and the final step, the storage of cylinders of feed material and the manufacture of fuel assemblies from fuel rods, have the characteristics typical of an item facility.

Generally, fuel fabrication plants operate on a three shifts per day mode with one to four shutdowns a year for a PIT or other reasons (depending on the type of plant and its annual throughput).

Containment and surveillance measures can only be used to a limited extent because of the specific features of the fabrication process and the arrangement of the material flow.

3.8.2. Structure of MBA

There is no standard pattern for the MBA structure. Some large plants are treated as a single MBA. The medium-size reference plant used as an example here has three MBAs:

- the feed storage area;
- the bulk material process area; and
- the assembling and product storage area.

The MBAs do not necessarily refer to locations but could also be regarded as functional units (e.g. designated according to types of materials).

The SPs usually coincide with the points at which the operator controls the technological process. There are considerable differences from one plant to another. An example of the SPs in one particular multi-MBA plant is given below.

MBA-1

Inventory KMPs – storage of feed material

Flow KMPs – receipts of feed material / reshipment of feed material / transfer from MBA-1 to MBA-2

C/S-SPs – storage of receipts

TABLE VII. EXAMPLES OF DIVERSION ANALYSES FOR FUEL FABRICATION PLANTS

Diversion	Concealment methods	Anomalies	Inspection activities[a]
This row applies to all the diversions listed below	Falsification of documents	Inconsistencies in documents	NMA I.2–I.8
1. Removal of nuclear material in all kinds of bulk form	Substitution of enriched U with natural or depleted U or inert material	Incorrect composition and/or enrichment	NMA I.8 – NDA C/S I.11 – Sealing
2. Removal of fuel rods	Substitution with dummies	Incorrect composition and/or enrichment	NMA I.8 – NDA
	Substitution with borrowed rods	Rods missing in another MBA	Simultaneous inspection
3. Removal of fuel assemblies	Changing of serial number and offering for double counting	Assemblies missing	NMA I.8
	Substitution with borrowed assemblies	Assemblies missing in another MBA	Simultaneous inspection

[a] See abbreviations on page 69.

MBA-2

Inventory KMPs – intermediate storage locations / various points of the conversion area / various stores (powder, pellets) / locations in the fabrication line and testing station / dry scrap: process vessels and storage / analytical laboratory: samples

Flow KMPs – receipt from MBA-1 / shipment of intermediate products / loading of rods, transfer from MBA-2 to MBA-3 / starting point of item accountancy / retransfer of rejected material from MBA-3 to MBA-2 / shipment of discards and scrap

C/S-SPs – intermediate storage of feed (seals) / UO_2 powder storage / UO_2 pellet storage

MBA-3

Inventory KMPs – fuel rods: inspection station, storage / fuel assemblies: assembly and inspection area, final storage

Flow KMPs – receipt from MBA-2 / rod scanning / shipment of fuel assemblies / receipt of fuel assemblies for reworking

C/S-SPs – finished rod storage / finished assembly storage.

3.8.3. Diversion assumptions

Owing to the characteristics of LEU and the accessibility of the process, the possibility of diversion of material by direct removal from storage or from the process line exists in LEU fuel fabrication plants at all times and at all stages. For LEU and natural and depleted uranium there is no difference between abrupt and protracted diversion as the detection time is assumed to be one year. Table VII shows simplified examples of diversion paths and concealment methods, the corresponding anomalies and the inspection activities intended to reveal them (see Sections 2.4 and 2.5).

3.8.4. Inspection goals

The accountancy verification goal is the capability of detecting the diversion during one year of an AVG quantity of nuclear material. This quantity is selected on the basis of the amount of material handled at the facility and the effect of measurement uncertainties. For most of the fuel fabrication plants presently under IAEA safeguards the accountancy verification goal quantity is smaller than or equal to one SQ. In a few cases of large plants the goal quantity is up to a few SQs. Timeliness guidelines: within 12 months.

3.8.5. Recording and reporting requirements

- At the facility: for [153] and [66], accounting and operating records supported by source documents
- ICR: for [153], 30 days after the end of the month in which the inventory change occurred
- MBR and PIL: for [153], for each MBA within 30 days after PIT;
  for [66], accounting and operating reports monthly.

A fuel fabrication plant is predominantly a bulk handling facility rather than a pure item facility and more detailed records are therefore required, the number and type depending on the diversity and accessibility of the nuclear material. The grouping of material into strata of batches[22] with similar physical and chemical characteristics facilitates statistical sampling. For each KMP, measurement results used for PIT should be recorded for each batch or item at each inventory location.

3.8.6. Special NMA features

The basic concept of NMA in the case of fuel fabrication plants consists in the careful verification of the material balance on the basis of random sampling. During the PIT performed by the plant operator the production is usually stopped for a few days, the nuclear material is collected at the inventory KMPs, all process lines are cleaned out, and scrap from them is measured. All material present is tagged and an itemized list is prepared to facilitate IAEA verification. The PIV is performed by IAEA inspectors at all inventory KMPs at the end of the PIT or concurrently with it, on the basis of a random sampling plan covering all strata of the material present.

The PIV makes use of weight checks of containers and attribute-testing and variables-testing methods. Specifically, for example, loaded fuel rods are checked to ensure that no pellets are missing and that the stated quantities are unbiased. Finished fuel assemblies are counted and identified against the operator's records. Attribute tests are carried out on UF_6 (or other feed) cylinders, powder, drums, pellets, rods, assemblies and scrap, by means of appropriate NDA techniques such as gamma spectrometry, while variables tests are carried

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[22] Batches are handled as units for NMA purposes. Examples: several drums of UO_2 powder, a tray of pellets, one UF_6 cylinder, one fuel assembly.

out on a random sample of powder, pellets and scrap. Rods can be directly and accurately measured by NDA if calibrated reference samples are available. This process and the measurement of fuel assemblies (using, for example, a neutron coincidence collar) are especially important for safeguards purposes because rods and assemblies are the final product of the fuel fabrication plant and will normally remain intact for a number of years.

The PIT performed by the operator will inevitably show a certain MUF. This may occur because of the holdups in the process equipment, operator measurement errors, losses during processing, etc. The MUF figures as calculated by the operator and as determined by the IAEA PIV are compared and carefully analysed in order to ascertain that they are not excessive.

During interim inspections the flow of nuclear material is verified by random sampling at flow KMPs and related inventory KMPs. Verification of receipts or shipments could also be performed at the supplying or receiving facility. In this case seals are used to ensure the identity of UF_6 cylinder or fuel assembly containers.

3.8.7. C/S measures

The application of C/S measures is often restricted to the sealing of:

- feed material (UF_6 cylinder) at the supplier's plant
- fuel assemblies or shipping containers before shipment to the power plant
- batches already measured during PIV
- nuclear material which could be left sealed between PITs.

Seals are also used to ensure during PIV that all items are inventoried without duplication and to ensure the integrity of samples taken for analysis. Temporary ASVS devices are used during PIV interruptions to ensure that no changes are made.

3.8.8. Routine inspection plan

Depending on the inventory and/or throughput of a LEU fuel fabrication plant, the IAEA conducts a certain number of inspections per MBP; one to two of these are used each year to verify the operator's PIT. Partial inventory verifications of various strata of the nuclear materials are taken cyclically, e.g. quarterly, on the occasion of interim inspections. Table VIII shows a typical annual inspection cycle. The total ARIE is 70 to 80 MDI/a. In some plants, verification and sealing of UF_6 cylinders received can be carried out during the interim inspections. There are cases where a large number of extra MDIs is required for this purpose; however, these 'man-days' require only brief access by IAEA inspectors to the UF_6 storage. For a large plant the ARIE can thus amount to

TABLE VIII. EXAMPLE OF A SIMPLIFIED ANNUAL INSPECTION PLAN FOR AN LEU FUEL FABRICATION PLANT

Inspection	Purpose/ Reason	MDI	Inspection activity[a]
1	PIV (all MBAs)	30	I.1–I.11
2–12	Interim inspection: partial PIV; flow verification, remaining NMA activities	40	I.1–I.11
	Verification and sealing of UF_6 cyclinders received	as required	I.11

[a] See abbreviations on page 69.

150–200 MDI. This compares with an MRIE of 280 MDI for a plant with an annual throughput of 500 t of uranium.

3.9. FUEL FABRICATION PLANTS – HEU AND MOX

Section 3.8 discussed fuel fabrication plants which handle LEU or natural or depleted uranium. There are a few fabrication plants under safeguards which process HEU (mainly for research reactors), or mixed uranium-plutonium oxide (e.g. for plutonium recycling into LWRs or LMFBRs). Such plants treat large quantities of materials which could be used for nuclear explosives without difficult conversion processes. Additional safeguards measures and further inspection effort have therefore to be concentrated on this stage of the fuel cycle. Furthermore a detection time of about 4 weeks is required with respect to direct-use materials. The AVG is selected on the basis of the amount of such materials handled at the facility and the effect of measurement uncertainties.

What has been said in Section 3.8 about plant features and diversion assumptions also applies largely to plants handling direct-use materials[23]. The main difference arises from the fact that in HEU/MOX fuel fabrication plants criticality considerations play an important role in the design of the plants and transport vessels, and also in the conduct of conversion, fuel assembly manufacture and scrap recovery. In the case of MOX or plutonium plants, there are severe constraints on the accessibility of the nuclear material owing to radiation and contamination hazards (the process takes place in gloveboxes or is remotely controlled in shielded cells). In addition to the measures discussed in Section 3.8, the following verification activities are foreseen. The safeguards approach includes two to four PITs (and PIVs) a year, made after each clean-out of the process lines, and interim inspections once or twice a month. Since it may not be practical for the operator to remove the nuclear material from process equipment to make it available for verification at intervals permitting a short detection time, unrestricted access of IAEA inspectors to the process area and to relevant operator data may be necessary at all times. Thus, data collection and non-destructive or destructive analysis and observation of material transfers by IAEA inspectors are linked to operating patterns established by the facility operator so that the desired detection capability can be achieved with minimum interference to normal plant operations.

The special features of this verification approach are as follows. The locations, compositions and quantities of all nuclear material are verified through PIVs after each of the two to four material balance periods during the year.

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[23] The fabrication process differs from that in LEU plants if metal fuel, e.g. for swimming pool type research reactors, is being produced.

These data serve as reference points for tracking the flow of materials within the plant during the operating period between successive PIVs. Starting from the reference points, procedures are established for the complete verification of material received before it is processed and of all products before they are dispatched. Seals are used extensively on feed material containers, in-process stores and products to the limit practicable, so as to permit expeditious reverification at each interim inspection.

Separate records are maintained by IAEA inspectors tracking the flow of materials through each separate process stage. These records are derived from the operator's production control records. During interim inspections, the inspectors verify the in-process inventory to the extent possible, without interrupting the fabrication process, examining one process stage after the other.

As far as possible, this schedule is set up to coincide with a break in process activities at each stage. The in-process verification includes visual item counting of material containers within each working area and the use of NDA to assess the amount of nuclear material in each stage. The quantity of nuclear material contained in batches transferred out of each stage is also verified and samples may be obtained as part of a continuous check on possible measurement bias. As the results of the sample analysis become available, they are used to complement the IAEA estimates based on NDA.

At the end of each inspection period, the inspectors summarize the findings for that period, investigate any problems that have arisen and make an assessment, based on the information collected and the observations of the process activities, whether it is likely that any diversion may have occurred during the period under consideration.

The inspection effort at fuel fabrication plants handling direct-use material is naturally higher than at LEU plants. Up to 600 MDI per year may be necessary, depending on the amount of nuclear material processed and the complexity of the plant.

3.10. REPROCESSING PLANTS

IAEA safeguards are currently applied routinely at six reprocessing plants. The design throughput of these plants ranges from small to modest in four cases and is of the order of 100 and 200 t of heavy metal in the other two. All plants use the Purex process. The safeguards approach is still evolving, especially that to be adopted for large commercial reprocessing plants (500–1000 t throughput), though these are not expected to come under IAEA safeguards for some years. Development work on methodology and instrumentation for such plants is under way. It covers advanced concepts such as near-real-time NMA, improved C/S measures, and more sophisticated process instrumentation. The advanced safeguards approach hopefully can undergo field testing and demonstration around 1985. This section considers the present safeguards approach at small-to-medium-size plants. The discussion relates specifically to the example of a particular plant with a 200 t design throughput per year.

3.10.1. Features of relevance to safeguards

Reprocessing plants are very significant from a safeguards point of view because they are designed to separate fissile material which could be used in a short period of time for nuclear explosives with a minimum of further work. Even the small plants considered here are capable of producing many kilograms of plutonium per year. A considerable inspection effort is therefore applied.

The receiving area of reprocessing plant presents no unusual inspection problems. The assemblies arriving at the plant are identified and stored temporarily under water: the safeguards situation at the pond is no different from that at the storage pond of a power plant. The next step is the dismantling and chopping of the fuel assemblies and rods, respectively; in these processes the integrity of items is lost. The chopped material is then sent to the dissolver and enters the liquid phase.

A major difficulty arises from the fact that in the process area of a reprocessing plant the nuclear material and most of the equipment containing fission products are inaccessible. Since the plant is dealing with highly irradiated fuel, the early process stages must be carried out behind shielding, normally concrete walls. The measurement vessels may likewise be hidden from view so that no direct observation is possible.

Another difficulty lies in the fact that the composition of the spent fuel arriving at a reprocessing plant is known only approximately from reactor calculations. The only opportunity that exists for determining the input of plutonium to the separation process is the analysis of content and composition of the dissolved fuel in the accountability tank. It is therefore necessary for this vessel to be carefully calibrated. The second KMP of great importance is the output accountability tank, which is also calibrated periodically. In order to strike a material balance for a campaign, representative samples are taken of input and output and all streams leaving the plant, and frequent assessments of the amount of materials present are made. At the end of each campaign (and at a minimum rate of twice a year), PIT and PIV are carried out after plant clean-out.

Since reprocessing plants operate in campaigns, usually round the clock for an extended period of time, there is a continuous flow of nuclear material. As a consequence of this mode of operation, of the complexity of the plant and of the large amounts of direct-use material handled, the continuous presence, or at any rate around-the-clock availability, of IAEA inspectors is necessary. During shutdowns, frequent inspections are made to check storage tank levels and records, and samples are taken for quick liquid density analysis.

3.10.2. Structure of MBA

Reprocessing plants are normally divided into three MBAs. If they include conversion of the separated plutonium from nitrate to oxide, this results in a fourth[24]. As an example, the MBA structure of a plant with three MBAs would be as follows: the first MBA covers the fuel assembly receiving and storage area, the chopping cell, the dissolver and the input accountability tank; the second consists of the chemical treatment area (including the plutonium product accountability tank), the waste treatment area and the laboratories; the third MBA covers the plutonium and uranium product storage[25]. An example of the SP structure of a three-MBA reprocessing plant is given below.

MBA-1

Inventory KMPs – storage of spent fuel assemblies

Flow KMPs – receipt of spent fuel assemblies / transfer from MBA-1 to MBA-2 / measured or estimated discards / receipt of recycled solution from MBA-2

C/S-SPs – spent fuel receiving and storage area (ASVS) / fuel transfer bay (ASVS) / krypton discharge and chopping cell radiation monitor

MBA-2

Inventory KMPs – in-process inventory / laboratories

Flow KMPs – receipts from MBA-1 / transfer of recycled solution to MBA-1 / measured discards / transfer of final products to MBA-3

Other SPs – various locations in the process area for observation of relevant instrument readings, measurements and calibrations

MBA-3

Inventory KMPs – storage of final uranium products / storage of final plutonium products[25].

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[24] In plants with low in-process inventory (at all times below one SQ) the conversion area may be included in the second MBA. Such facilities also may operate without an output accountability tank.

[25] In some cases the plutonium cannot be stored and is shipped from the second MBA.

Flow KMPs	– receipt of final products from MBA-2 / shipment of final products
C/S-SPs	– storage area (ASVS) / valves and transfer lines (seals) / plutonium product containers (seals) / uranium product containers (seals).

3.10.3. Diversion assumptions

For reprocessing plants a variety of diversion hypotheses have to be taken into account. The possibilities range from the direct removal of material (such as spent fuel assemblies or separated plutonium) from their respective stores to the subtle case of undeclared withdrawal of part of the process flow through some of the numerous pipes which form part of the plant. Except in the case of whole spent fuel assemblies, these activities could be carried out either as abrupt or as protracted diversion. Table IX shows simplified examples of diversion paths and concealment methods, the corresponding anomalies and the inspection activities intended to reveal them (see Sections 2.4 and 2.5).

3.10.4. Inspection goals

The accountancy verification goal is the capability of detecting the diversion during a year of an AVG quantity of nuclear material. This quantity is selected on the basis of the amount of material handled at the plant and the effect of measurement uncertainties. Timeliness guidelines:

- within 4 weeks for separated plutonium;
- within 3 months for irradiated fuel; and
- within 12 months for separated uranium.

3.10.5. Recording and reporting requirements

- At the facility: for [153] and [66], accounting and operating records supported by source documents
- ICR: for [153], 30 days after the end of the month in which the inventory change occurred
- MBR and PIL: for [153], within 30 days after each PIT for each MBA;
  for [66], accounting and operating reports monthly.

A reprocessing plant is predominantly a bulk handling facility rather than a pure item facility, and more detailed records are necessary owing to the complexity of the plant and the large amounts of direct-use material. This is true in particular for operational data relating to: volume, density and concentration for each transfer of nuclear material; calibration of instruments and

TABLE IX. EXAMPLES OF DIVERSION ANALYSES FOR REPROCESSING PLANTS

Diversion	Concealment methods	Anomalies	Inspection activities[a]
This row applies to all the diversions listed below	Falsification of documents	Inconsistencies in documents	NMA I.2–I.8
1. Unrecorded transfer of fuel assemblies to chop and leach	Substitution in the storage with dummies	Incorrect composition and/or enrichment	NMA I.8 – NDA
		C/S devices indicate anomaly	C/S I.10 – ASVS
2. Removal of fuel assemblies in transfer	Use of irregular fuel paths	C/S devices indicate anomaly	C/S I.10 – ASVS
3. Fuel not fully dissolved, or removal of chopped pieces (for unrecorded dissolution later)	Substitution of hulls by dummies	Abnormal Pu and U content of hulls	C/S I.10 – Observation of transfer to storage NMA – NDA
4. Liquid from dissolver by-passes accountability tank, or	Piping inaccessible during operation	Inconsistency of piping with design	Design verification
Unrecorded transfers from the tank to process		Departure from normal operation mode	C/S I.10 – Sealing of valves, radiation monitors

		Discrepancies in total U and Pu content	NMA I.7 – Continuous material balance check across the processing area
5. Incorrect statement of volume of Pu and U concentration of transfers to the process area	Inaccurate calibration or tampering with instruments	Incorrect measurements	NMA I.8 and I.12 – Verification of calibration and measurements
	Use of non-representative samples	Samples untypical	C/S I.10 – Observation of sample taking
	Falsification of chemical analysis	Results incorrect	Independent analysis of samples[b]
	Recycle of acid, etc., containing unreported Pu and U	Recycled fluid contains Pu or U; see also case 4	Independent analysis of recycled fluid[b]
6. Removal of solutions through pipework which does not form part of normal declared production stream	Piping inaccessible during operation	as in case 4	as in case 4
	Recording of wrong Pu and U content of wastes	Incorrect Pu or U content of wastes	NMA I.7 – Verification of waste streams, independent analysis of samples
	Invention of accidental losses	No traces of spills or discharges	C/S I.10 – Observation of emergency, cleaning, or recovery procedures

TABLE IX (cont.)

Diversion	Concealment methods	Anomalies	Inspection activities[a]
	Recording of wrong Pu and U hold-up in process vessels during inventory taking	No abnormal hold-ups present	C/S I.10 – Observation of clean-out procedures; NMA I.8 -- Measurement of Pu and U involved
7. Product by-passes output accountability tank or unrecorded transfers from the process area	as in case 4	as in case 4	as in case 4
8. Incorrect statement of volume or Pu and U concentration of transfers from the process area	as in case 5	as in case 5	as in case 5
9. Unrecorded shipments of Pu and U from the storage area	as in first row	as in first row	as in first row

[a] See abbreviations on page 69.

[b] In the Safeguards Analytical Laboratory (SAL).

the accuracy of measurements; sampling and sample analyses; and derived estimates of random and systematic measurement errors.

3.10.6. Special NMA features

Continuity of knowledge of flow and inventory of nuclear material is essential because of the operational characteristics of the plants. This requires special NMA techniques with heavy reliance on measurements and their evaluation.

The transfer of spent fuel assemblies received from power plants to the storage pond and then on to the chopping cell presents no particular problems. The pond is covered by C/S, and flow verification is done either by sealing spent fuel containers at the power plant and checking the seals at the reprocessing plant or by verifying receipts.

The determination of the actual content of the spent fuel assemblies and in particular of the input to the process is a complex task but one of primary importance. The first and only point in the fuel cycle permitting this determination is the accountability tank which receives the dissolved fuel. The measurements are cross-checked with those on the output accountability tank. Provision is made for the continuous presence of IAEA inspectors during these measurements. A basic requirement is careful periodic calibration of the accountability tanks, i.e. determination of the volume as a function of the liquid level with allowance for such factors as changes in geometry as a result of changes in the temperature or the weight of the contents. An equally essential task is the determination of the plutonium content of the tank by measurement of the volume of the solution (related to the length of a manometer column) and the concentration of uranium and plutonium in the liquid (related to the specific gravity of the liquid and the results of analysis of samples). Measurement inaccuracies are reduced by isotopic correlation methods (e.g. Pu/U ratio and ^{235}U depletion), the addition of spiking substances, etc.

It is nearly impossible to ensure that there exists no by-pass line out of the process MBA. Therefore one of the essential measures is continuous material balance checks across the processing area. To this end, in addition to the verification of the plutonium and uranium content of the accountability tank, all possible sidestreams such as for example nuclear material remaining in the leached hulls or contained in recycled nitric acid have to be taken into account. Analysis of samples is foreseen in these cases.

Another important KMP corresponds to plutonium output from the process MBA. Where the output is in the form of plutonium nitrate the quantity determination is again dependent on source data relating to volume determination and the measurement of the plutonium concentration in the output accountability tank. The uranium output has to be verified and compared to the plutonium output and the Pu/U ratio found in the input to the plant.

If the plutonium nitrate is converted into plutonium oxide, a separate process MBA usually has to be established. The measurement principles for receipts into and shipments out of this MBA are, mutatis mutandis, the same as for the first process MBA.

The plutonium product storage at the output of the reprocessing plant has to be verified frequently with a high confidence level. Interim inventory verifications should be repeated every two to three weeks. Shipments from the product storage should be sealed and rechecked immediately after arrival at the receiving MBA.

Inspection results and safeguards conclusions must be worked out continuously on the site to assure short detection times. Most analytical results derived by the operator of a reprocessing plant are established in at least two stages. For process purposes the operator needs analytical results within a few hours, but can accept lower accuracy. Analyses of that kind are usually called 'process analyses'. All analyses essential for accountancy are repeated with much higher precision, but with a delay of several days, or exceptionally weeks. This type of analysis is usually called 'accountability analysis'. Inspection results should be evaluated continuously using a similar two-stage procedure. The first stage is based on observation of a process analysis while at the second stage a correction is introduced on the basis of the verification of the accountability analysis. Only the second stage results are later compared with the official reports sent to IAEA Headquarters.

3.10.7. C/S measures

- Application of ASVS and seals in the receiving storage bay
- Observation by IAEA inspectors of calibrations, measurements and sampling by the operator, and relevant process instrument readings
- Sealing of valves, use of radiation monitors
- Observation by IAEA inspectors of emergency, cleaning and recovery procedures in the event of accidental loss of nuclear material
- Observation by IAEA inspectors of clean-out procedures before PIT
- Application of ASVS and seals in the product storage and shipment area.

3.10.8. Routine inspection plan

Between any two compaigns, normally twice a year, PIT and PIVs are conducted after careful clean-out of the plant. During reprocessing campaigns, IAEA inspectors have continuous access to all SPs[26]. For 24-hour coverage

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[26] Under special conditions (low in-process inventory) interim inspections are made between PIVs.

this requires 3 MDI per day and per inspector (see footnote 11 on page 15). During shutdowns the IAEA carries out frequent interim inspections to:

- check the plutonium storage area where applicable
- witness inventory changes at KMPs
- check seals and cameras
- check instruments and charts for undeclared operation
- audit books (monthly).

Table X shows a typical annual inspection cycle at a reprocessing plant. The inspection effort required depends on the mode of operation of the plant. In the example given, 250 days of operation during the year are assumed. In this case the total ARIE corresponding to present practice and existing techniques is about 850 MDI/a. This compares with an MRIE of about 1300 MDI/a for an annual plutonium throughput of 2 t.

3.11. ENRICHMENT PLANTS

The IAEA has only limited experience with enrichment plants. Inspections are made at a few plants in non-nuclear-weapon States which use the gas centrifuge process to produce LEU, and these inspections have been restricted until now to locations outside the cascade hall. Recently, with the support of experts from Member States (the 'Hexapartite Safeguards Project'), the so-called 'limited-frequency unannounced access' (LFUA) model was developed for the cascade area, thus providing coverage for the whole plant. It is expected that in the near future commercial enrichment plants in nuclear-weapon States will also come under safeguards. As gas centrifuge plants for LEU production will remain for the foreseeable future the main type covered by IAEA safeguards, the following discussion is restricted to them. As implementation of the LFUA model is under negotiation and no practical experience is available at present, the following discussion is to be considered as preliminary[27].

3.11.1. Features of relevance to safeguards

The feed for the plants considered here is usually natural uranium, the product is LEU, and depleted uranium remains as tails. The plant consists of a multistage arrangement of centrifuges ('the cascade'), a feed and withdrawal station connected to the cascade, and storages for feed, product and tails. The

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[27] A plant for separating isotopes of a nuclear material is considered as a 'principal nuclear facility' in [66]; however this document contains no special provisions for enrichment plants.

TABLE X. EXAMPLE OF A SIMPLIFIED ANNUAL INSPECTION PLAN FOR A REPROCESSING PLANT

Inspection frequency	Purpose/Reason	MDI	Inspection activity[a]
Twice a year	PIV (all MBAs)	20	I.1–I.11
During campaign	Continuous inspection: flow verification; remaining NMA and C/S activities	750[b]	I.1–I.11
During shutdown	Interim inspections: partial PIV (Pu); flow verification; calibrations; surveillance	80[b]	I.1–I.11

[a] See abbreviations on page 69.

[b] For reprocessing campaigns totalling 250 days a year.

[c] For shutdown during the rest of the year (115 days).

nuclear material remains in a single chemical form – high purity uranium hexafluoride (UF_6) – in all parts of the plant.

The main feature of safeguards relevance consists in the fact that enrichment plants are in principle capable of producing HEU (including weapons grade material) starting from natural uranium. The plants considered here are designed to enrich uranium up to 5% ^{235}U for commercial power reactors (mainly LWRs). In order to produce higher grades of enrichment, either a change of the design of the plant or of its operation would be necessary. Unreported modifications of this kind cannot be excluded from the diversion hypotheses. Also, the diversion of feed, product, or tails has to be taken into account in the design of the safeguards approach.

Concerning the latter assumption, it is to be noted that enrichment plants operate on bulk material. Verification by NMA is to a certain extent facilitated by the fact that the amount of UF_6 contained in the cascade is rather small, whereas the main part of the inventory remains outside the cascade and is handled and stored in large steel cylinders. After verification of the content and sealing, these cylinders can be treated as items.

Unreported production of HEU would require rearrangement of the gas flow in such a way as to decrease the number of centrifuges in parallel and to increase the number of stages in series. High enriched uranium could also be produced by repeated batch recirculation of UF_6, a substantial change in the declared operation mode which would require the use of alternative feed and take-off points or rearrangements of the existing connections.

Verification that no HEU is produced can best be obtained by inspectors having access to the cascade hall[28]. However, there is sensitive information in this case which has to be protected for commercial and non-proliferation reasons. The solution developed to allow for these concerns is the LFUA model (see Section 3.11.7).

Inspection activities outside the cascade hall follow the standard pattern for LEU in bulk or item facilities.

3.11.2. Structure of MBA

Enrichment plants are usually divided into several MBAs. In the example given below three MBAs are foreseen[29]. The first includes areas for shipment

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[28] The alternative is to treat the cascade hall as an exclusion area not accessible to IAEA inspectors and to establish a special MBA around the hall [153/para.46(b)]. In this case a complex, costly and intrusive system of C/S measures ('perimeter control') would have to be established around the cascade hall.

[29] Depending on the actual design of the enrichment plant, two-MBA arrangements are also conceivable, the first MBA including all storage areas and the second covering the whole process area.

TABLE XI. EXAMPLES OF DIVERSION ANALYSES FOR ENRICHMENT PLANTS

Diversion	Concealment method	Anomalies	Inspection activities[a]
This row applies to all the diversions listed below	Falsification of documents	Inconsistencies	NMA I.2–I.8
1. Removal of enriched UF_6	Substitution with feed, tails or inert material	Cylinders with incorrect enrichment	NMA I.11 – NDA C/S I.11 – Sealing
	Substitution with borrowed material	Material missing at another MBA	Simultaneous inspection
2. Enrichment of unreported feed	Operation between inspections only	Output higher than stated	NMA I.2–I.8 C/S I.11 – Sealing
		Material missing at another MBA	Simultaneous inspection
3. Production of HEU by change of cascade configuration or operation mode	Restoration before inspections	Design or operation changes, presence of HEU	According to LFUA model
		Radiation level higher than normal	NMA I.11 – NDA
		Material balance affected	NMA I.2–I.8

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[a] See abbreviations on page 69.

and storage of feed; the second includes the process area (the cascade and the blending and homogenization station). The third MBA is composed of the product and tails collection station, storage, and shipping area. A typical set of SPs is as follows:

MBA-1

Inventory KMPs – receiving and storage locations for feed UF_6 / feed UF_6 loading stations / emptied UF_6 cylinders

Flow KMPs – receipt of feed UF_6 and shipment of emptied cylinders / transfer of vaporized feed UF_6 to MBA-2

C/S-SPs – storage area as appropriate

MBA-2

Inventory KMPs – process area, verifiable material / intermediate storages / desublimers for products / desublimers for tails / cascade area / analytical laboratories, waste treatment area

Flow KMPs – receipt of vaporized product UF_6 feed from MBA-1 / transfer of product and tails UF_6 to MBA-3 / measured discards

C/S and other SPs– process area as appropriate (measurements, calibrations, etc.)

MBA-3

Inventory KMPs – product stations / tails stations / product storage and shipping stations / tails storage and shipping stations

Flow KMPs – receipt of product and tails UF_6 from MBA-2 / shipment of product and tails cylinders

C/S-SPs – storage area as appropriate (ASVS, sealing).

3.11.3. Diversion assumptions

Table XI shows simplified examples of diversion paths and concealment methods, the corresponding anomalies and the inspection activities[30] intended

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[30] Details of the LFUA model still have to be developed and agreed.

TABLE XII. EXAMPLE OF A SIMPLIFIED ANNUAL INSPECTION PLAN FOR AN ENRICHMENT PLANT

Inspection	Purpose/Reason	MDI	Inspection activity[a]
1	PIV (feed, product, waste)	50	I.1–I.11
2–11	Interim inspections	54	NMA I.1–I.8 C/S I.11 – Sealing
12–23[b]	Limited frequency unannounced inspections (may be combined with interim inspections)	12	LFUA activities

[a] See abbreviations on page 69.

[b] This example assumes twelve LFUA inspections per year.

to reveal them (see Sections 2.4 and 2.5). In case where HEU is produced one or more of the following anomalies are to be expected:

- significant variations in UF_6 flow or concentration at feed and withdrawal stations
- changes in declared UF_6 piping arrangement
- existence of additional storage, feed and withdrawal stations/facilities or rearrangements at the existing connections
- a radiation field indicating the presence of HEU
- variations in the ratio of product/tails.

3.11.4. Inspection goals

For plants using ultracentrifuge technology and declared to produce LEU enriched up to 5% ^{235}U, the same procedures are applied to determine the inspection goals as in other LEU bulk handling facilities (see Section 3.8.4). In addition, sufficient assurance should be achieved through permitting LFUA by IAEA inspectors to the cascade halls and through NMA verification that uranium at an enrichment level higher than that declared is not produced in such a facility.

3.11.5. Recording and reporting requirements

- At the facility: accounting and operating records supported by source documents
- ICR: for [153], 30 days after the end of the month in which an inventory change occurred
- MBA and PIL: for [153], within 30 days after each inventory taking, usually once a year.

3.11.6. Special NMA features

The physical inventory of uranium (feed, product and tails) is taken simultaneously in all MBAs at least once a year. This implies transferring all the feed flow to measured containers and all product and tails flows to emptied desublimers. Thus, all nuclear material, except for material in the cascade or in the cascade halls, is then contained in standard steel cylinders or other containers. These are itemized and an itemized inventory list is prepared for the IAEA PIV. Verification consists in counting items and random selection of cylinders and other containers which are identified, weighed and attribute-checked by NDA. In addition UF_6 samples are taken for chemical analysis.

3.11.7. C/S measures

The sealing of UF_6 cylinders is used extensively in order to avoid frequent reverification of their content. The cascade hall is to a large extent not amenable to the use of C/S measures; however, seals may be applied to some flanges in the piping and to valves which remain normally closed or open. In accordance with the LFUA model, these inspections are made at short notice. The frequency is determined by the estimated time necessary to change the arrangement or the operating mode of the cascade in order to produce HEU and the time necessary to produce one SQ of HEU[31].

Some or all of the following LFUA inspection activities are foreseen, depending on the technical features of the plant considered:

- Visual observation, comparing the configurations and features of the cascade and the pipe penetrations through the walls of the cascade hall with design drawings, photographs or other records
- NDA measurements and radiation monitoring to assess the enrichment of the gas flow
- Sampling of UF_6 at certain points
- Application of seals at certain flanges, valves, etc.

3.11.8. Routine inspection plan

At least once a year a total PIV should be carried out. Owing to the continuous change of the inventory, 15 interim inspections dealing mainly with flow verification and quick inventory examinations and up to 12 LFUA inspections are foreseen for an enrichment plant with a capacity of up to 1000 t SWU/a[32]. Table XII shows a typical inspection cycle. The total ARIE for the example considered runs to about 116 MDI/a. This compares with an MRIE of about 180 MDI/a.

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[31] Estimates of the required average inspection frequency range from 4 to 12 times per year depending on the design of the plant.

[32] 1 t SWU is necessary to produce from natural uranium about 0.23 t uranium enriched to 3%.

LIST OF INSPECTION ACTIVITIES

I.1. Follow-up actions
I.2. Accounting records examination
I.3. Operating records examination
I.4. Reconciliation of accounting and operating records
I.5. Comparison of records and reports
I.6. Updating of the book inventory
I.7. Inventory change (flow) verification
I.8. Inventory verification
I.9. Verification at special strategic points
I.10. Application and use of surveillance
I.11. Application and use of seals
I.12. Verification of adequacy of the operator's measurement system
I.13. Other inspection activities.

ABBREVIATIONS

a	year
ARIE	Actual routine inspection effort
ASVS	Automatic surveillance system
AVG	Accountancy verification goal
C/S	Containment and surveillance
e	Effective kilogram
E	Inventory, or annual throughput or production (kg)
HEU	High enriched uranium
ICR	Inventory change report
INFCE	International nuclear fuel cycle evaluation
INFCIRC	Information circular
I.X	Inspection activity No. X
KMP	Key measurement point
LEU	Low enriched uranium
LFUA	Limited frequency unannounced access
LMFBR	Liquid metal cooled fast breeder reactor
LWR	Light water reactor
MBA	Material balance area
MBP	Material balance period
MBR	Material balance report
MDI	Man-days of inspection
MOX	Mixed oxide (U and Pu)
MRIE	Maximum routine inspection effort
MUF	Material unaccounted for
MW(e)	Megawatt electric
MW(th)	Megawatt thermal
NDA	Non-destructive assay
NMA	Nuclear material accountancy
PIL	Physical inventory listing
PIT	Physical inventory taking
PIV	Physical inventory verification
Pu	Plutonium
SAL	Safeguards Analytical Laboratory (IAEA)
SP	Strategic point
SQ	Significant quantity
SSAC	State's system of accounting for and control of nuclear material
SWU	Separative work unit
TV	Television
U	Uranium
UF_6	Uranium hexafluoride
UO_2	Uranium dioxide
U_3O_8	Yellow cake

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