Safeguards Techniques and Equipment

2003 Edition

International
Nuclear Verification
Series No. 1
(Revised)

IAEA
International Atomic Energy Agency

SAFEGUARDS TECHNIQUES AND EQUIPMENT

2003 Edition

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BANGLADESH
BELARUS
BELGIUM
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHILE
CHINA
COLOMBIA
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
LATVIA
LEBANON
LIBERIA
LIBYAN ARAB JAMAHIRIYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITIUS
MEXICO
MONACO
MONGOLIA
MOROCCO
MYANMAR
NAMIBIA
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
PAKISTAN
PANAMA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
SAUDI ARABIA
SENEGAL
SERBIA AND MONTENEGRO
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIETNAM
YEMEN
ZAMBIA
ZIMBABWE

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".

Printed by the IAEA in Austria
August 2003
IAEA/NVS/1 (Revised)

INTERNATIONAL NUCLEAR VERIFICATION SERIES
No. 1 (Revised)

SAFEGUARDS TECHNIQUES AND EQUIPMENT

2003 Edition

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2003

IAEA Library Cataloguing in Publication Data

Safeguards techniques and equipment. — Rev. ed. — Vienna :
International Atomic Energy Agency, 2003.
p. ; 24 cm. — (International nuclear verification series, ISSN, 1020-6205 ; no. 1 (Revised))
IAEA/NVS/1/(Revised)
ISBN 92–0–109403–5
Includes bibliographical references.

1. Nuclear industry—Materials management. 2. Nuclear reactors—Materials—Analysis. 3. Nuclear reactors—Containment. 4. Environmental sampling. I. International Atomic Energy Agency. II. Series.

IAEAL 03–00330

FOREWORD

The 1990s saw significant non-proliferation related developments in the world, resulting in a new period of safeguards development. Over several years an assessment was made of how to strengthen the effectiveness and improve the efficiency of IAEA safeguards. In May 1997 this culminated in the adoption by the IAEA Board of Governors of a Protocol Additional to Safeguards Agreements which significantly broadens the role of IAEA safeguards. As a consequence, the IAEA safeguards system entered a new era.

Together with the introduction of the strengthened safeguards systems, in 1997 the IAEA began to publish a new series of booklets on safeguards, called the International Nuclear Verification Series (NVS). The objective of these booklets was to help in explaining IAEA safeguards, especially the new developments in safeguards, particularly for facility operators and government officers involved with these topics.

The current booklet, which is a revision and update of IAEA/NVS/1, is intended to give a full and balanced description of the techniques and equipment used for both nuclear material accountancy and containment and surveillance measures, and for the new safeguards measure of environmental sampling. A completely new section on data security has been added to describe the specific features that are included in installed equipment systems in order to ensure the authenticity and confidentiality of information. As new verification measures continue to be developed the material in this booklet will be periodically reviewed and updated versions issued.

CONTENTS

1. INTRODUCTION

The IAEA has the task of providing continuing assurance to the international community that States that have entered into safeguards agreements with the IAEA are meeting their obligations. This requires that assurance be given that any diversion of safeguarded nuclear material to a proscribed military purpose would be detected and that all nuclear material in the State has been declared. To this end, the IAEA must be able to verify the correctness and completeness of the statement that it receives from States concerning the nuclear materials included in safeguards agreements.

In addition, the IAEA has the right and obligation to verify States' commitments under their safeguards agreements and, where applicable, Additional Protocols. In particular, as part of the implementation of Additional Protocol and Integrated Safeguards, inspectors must be able to confirm the absence of undeclared nuclear materials and activities during the inspections and complementary access visits.

The basic verification measure used by the IAEA is nuclear material accountancy. In applying nuclear material accountancy, IAEA safeguards inspectors make independent measurements to verify quantitatively the amount of nuclear material presented in the State's accounts. For this purpose, inspectors count items (e.g. fuel assemblies, bundles or rods, or containers of powdered compounds of uranium or plutonium) and measure attributes of these items during their inspections using non-destructive analysis (NDA) techniques, and compare their findings with the declared figures and the operator's records. The purpose of this activity is to detect missing items (gross defects). The next level of verification has the aim of detecting whether a fraction of a declared amount is missing (partial defect) and may involve the weighing of items and measurements with NDA techniques such as neutron counting or γ ray spectrometry. These techniques are capable of measuring the amount of nuclear material with an accuracy in the order of a few per cent. For detecting bias defects, which would arise if small amounts of material were diverted over a protracted length of time, it is necessary to sample some of the items and to apply physical and chemical analysis techniques having the highest possible accuracy, typically less than one per cent. In order to apply these destructive analysis (DA) techniques, the IAEA requires access to laboratories which use such accurate techniques on a routine basis.

Containment and surveillance (C/S) techniques, which are complementary to nuclear material accountancy techniques, are applied in order to maintain continuity of the knowledge gained through IAEA verification, by giving assurance that nuclear material follows predetermined routes, that the integrity of its containment remains unimpaired and that the material is accounted for at the correct measurement points. They also lead to savings in the safeguards inspection effort, e.g. by reducing the frequency of accountancy verification. A variety of C/S techniques are used, primarily optical surveillance and sealing. These measures serve to back up nuclear material accountancy by providing means by which access to nuclear material can be monitored and any undeclared movement of material detected.

Unattended and remote monitoring is a special mode of application of NDA or C/S techniques, or a combination of these, that operates for extended periods of time without inspector access. In remote monitoring, the unattended equipment transmits the data off-site. For unattended and remote monitoring, additional criteria must be met, including high reliability and authentication of the data source. Data communication costs have dropped dramatically in recent years. Consequently, expanded deployment of unattended and remote monitoring systems has become an increasingly important element of IAEA safeguards in efforts to maintain or increase effectiveness without increasing inspector resources or overall costs.

Data security is an important feature of unattended and remote monitoring systems. In fact, those types of safeguards systems, permanently installed at facilities and periodically visited by inspectors, transmit data between the components of different systems and between systems and IAEA headquarters through insecure transmission paths. These data need to be verified to guarantee their authenticity and may need to be encrypted to avoid disclosure of specific information and/or to ensure confidentiality to the Member States.

Environmental sampling, which allows detection of minute traces of nuclear material, was added to the IAEA's verification measures in the early 1990s as a powerful tool for detecting indications of undeclared nuclear activities. The non-detection of minute traces of a specific nuclear material can provide assurance that there were no activities utilizing the material in the area where the environmental samples were taken.

The complexity and diversity of facilities containing safeguarded nuclear material require a correspondingly diverse set of verification techniques and equipment. Table I lists the main types of facility where inspections are performed and the primary verification techniques that are implemented at these facilities.

Development of equipment and techniques for safeguards is continuing with the help of national support programmes that assist the IAEA in keeping pace with the evolution of new technology. The IAEA defines the safeguards needs, co-ordinates the support programmes, and tests and evaluates the techniques and the resulting equipment being developed. All aspects of

TABLE I. MAIN TYPES OF FACILITY UNDER IAEA SAFEGUARDS
(data based on 2002 Safeguards Implementation Report)

Enrichment plants	Fuel fabrication plants	Power reactors and separate storage facilities	Spent fuel reprocessing plants
Number of facilities safeguarded in 2002			
10	41	239 power reactor units 80 separate storage facilities	6
Main techniques deployed			
Materials: UF$_6$ Gamma ray spectrometry Weighing	Materials: U and Pu oxides, MOX Gamma ray spectrometry Neutron counting Destructive analysis Isotopic determination	Materials: Spent fuel Cerenkov glow detection Gross γ ray and neutron detection	Materials: U and Pu nitrates Destructive analysis Neutron counting

IAEA summary statistics for 2002 (approximate numbers)

2 430	inspections at 603 facilities and 706 NDA systems used in 1 639 inspections at 553 facilities
766	DA samples analysed 1581 analytical results were reported
489	video cameras deployed for optical surveillance
24 572	seals detached and verified
232	environmental samples taken in 11 enrichment installations and 36 other installations, including facilities with hot cells

equipment performance are evaluated, including compliance with specifications, reliability and transportability and, most importantly, suitability for use by IAEA inspectors in nuclear facilities. The IAEA has an established quality assurance procedure to authorize equipment and software for routine inspection use.

The equipment and techniques highlighted in this booklet are those in frequent use for inspection purposes or in the late stages of development. The overall objective of this publication is to provide a comprehensive overview of the techniques and equipment underlying the implementation of IAEA safeguards.

2. NON-DESTRUCTIVE ANALYSIS

2.1. GAMMA RAY SPECTROMETRY

2.1.1. Gamma emission and detection of nuclear materials

Most nuclear materials of concern in IAEA safeguards emit γ rays that can be used for NDA of the materials. Gamma rays have well defined energies that are characteristic of the isotopes emitting them. Determination of the γ ray energies serves to identify the isotopic composition of the materials. When combined with a measurement of intensities, the γ ray energies can provide quantitative information on the amount of material that is present:

(a) Enriched uranium fuel, for example, has a strong 186 keV γ ray associated with the alpha decay of ^{235}U, and the ^{235}U enrichment can be verified by measuring this γ ray.
(b) Plutonium samples generally contain the isotopes ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu as well as decay products, which give rise to a highly complex mix of characteristic γ ray energies. Plutonium spectra can be analysed to determine the isotopic composition.
(c) The date of discharge of irradiated fuel from a reactor can be verified by measuring the relative intensities of γ rays associated with fission and activation products. The 662 keV γ ray from ^{137}Cs is particularly important for this type of determination.

To detect γ rays, the radiation must interact with a detector to give up all or part of the photon energy. The basis of all γ ray detector systems is the collection of this liberated electrical charge to produce a voltage pulse whose amplitude is proportional to the γ ray energy. In a γ ray spectrometer, these pulses are sorted according to amplitude (energy) and counted using appropriate electronics, such as a single or multichannel analyser. With a multichannel analyser, the γ rays from different energies can be displayed or plotted to produce a γ ray energy spectrum which provides detailed information on the measured material.

The γ ray detectors most commonly used are either scintillators (usually activated sodium iodide (NaI) crystals) or solid state semiconductors (usually high purity germanium (HpGe) and cadmium–zinc–telluride (CdZnTe) crystals).

(1) The NaI detectors can be made with large volumes and generally have higher γ ray detection efficiencies than Ge detectors. Their safeguards applications include, for example, the verification of ^{235}U enrichment in fresh fuel as well as the presence of spent fuel through detection of fission product γ radiation. Their ability to distinguish between γ rays of different energies, however, is relatively poor and of the three types of detector they have the worst energy resolution.

(2) Germanium detectors have far superior energy resolution to NaI detectors and are better suited to the task of resolving complex γ ray spectra and providing information about the isotopic content of materials. The Ge detectors used by the IAEA range in size from small planar types to large (80–90 cm^3) coaxial detectors. A disadvantage of these detectors is that they must be operated at a very low temperature, which is usually achieved by cooling with liquid nitrogen.

(3) Standard CdZnTe detectors (and CdTe detectors) do not need cooling and of the three detectors they have the highest intrinsic detection efficiency. Recent progress in fabrication techniques has substantially improved CdZnTe resolution. Until 1997 the standard volumes available were relatively small (20 and 60 mm^3), but now relatively large 500 mm^3 and 1500 mm^3 CdZnTe detectors are available. The portability and small size of CdZnTe and CdTe detectors have made them especially suitable for use in a wide range of applications, including use in confined spaces such as in situ verification of fresh fuel assemblies whose design permits insertion of only a small detector probe into the assembly interior and of spent fuel bundles stored underwater in closely packed stacks.

Figure 1 illustrates the capabilities of various types of detector with low, medium and high resolution. Several γ ray spectrometers (multichannel analysers and detectors) that differ mainly in their resolution and analytical capability are being used for safeguards purposes. These are summarized in Table II and described below.

2.1.2. Hand-held multipurpose gamma spectrometry

HM-5 (fieldSPEC). This device is the successor to the Hand-held Assay Probe (HM-4). Due to technological progress, the HM-5 (Fig. 2) is far superior in design and performance to its predecessor. The HM-5 is a modern, hand-held, digital gamma spectrometer combining various functions such as dose rate measurement, source search, isotope identification, active length determination for fuel rods and assemblies, and Pu/U attribute verification.

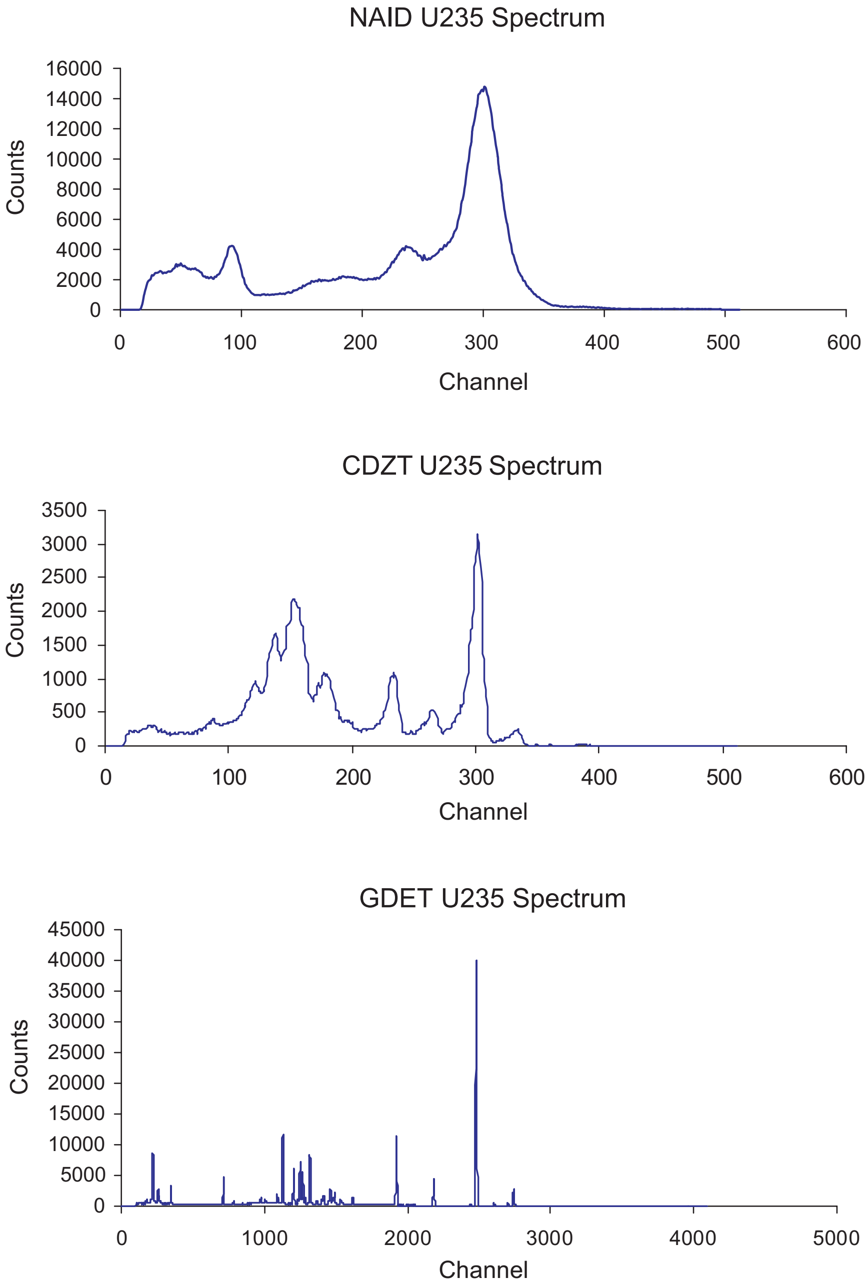


FIG. 1. Comparison of γ ray spectrometric performance of various types of detector (low, medium and high resolution).

TABLE II. GAMMA RAY SPECTROMETERS

Code	Equipment name	Primary applications
HM-5	Hand-held Assay Probe	Qualitative determination of the presence of U, Pu and other isotopes
IMCN, IMCC, IMCG	I-2000 Multichannel Analyser (IMCA) used with NaI or CdZnTe or Germanium Detector	Verification of U enrichment, spent fuel and Pu isotopic composition
MMCN, MMCC, MMCG	Miniature Multichannel Analyser (MMCA) used with NaI or CdTe or Germanium Detector	Verification of U enrichment and spent fuel

The basic HM-5 modular design includes an NaI detector. For special applications the NaI detector can be replaced with a more stable, higher resolution CdZnTe detector. Up to 50 gamma spectra, each with 1024 channels, can be stored in the non-volatile memory of the HM-5 and later be transferred to a computer for further processing or plotting.

With such versatility, the HM-5 is used for traditional safeguards inspections and for investigations under the conditions of the Additional Protocol. The HM-5 is also particularly useful for law enforcement services to detect and identify nuclear and radioactive materials being smuggled across borders.

FIG. 2. The HM-5 fieldSPEC.

2.1.3. Multichannel analysers

IMCA (InSpector2000). The new InSpector 2000 (I-2000) multichannel analyser (IMCA), based on digital signal processing (DSP) technology, can be combined with the various types of detector that are now used for inspection purposes, namely HpGe, CdZnTe and NaI, allowing high, medium and low resolution spectrometry. The device provides unsurpassed count rate and resolution performance coupled with environmental stability in a very small and compact package. The IMCA (Fig. 3) follows the ongoing evolution in the MCA market, including the latest developments in this domain. Its high performance is derived from the application of DSP technology, which digitizes preamplifier signals at the very beginning of the signal processing chain. The use of analog circuitry in the instrument is reduced, resulting in a compact instrument that has increased stability, accuracy and data reproducibility while improving the overall signal acquisition performance.

Because the I-2000 is a commercially available instrument that is being used worldwide, the IAEA can use I-2000 based operator equipment for inspection purposes. Use of such operator equipment is contingent on the IAEA being able to authenticate the data and on applicability of common software. The transition to this new equipment has enabled the IAEA to phase out obsolete equipment such as the old InSpector MCA and the PMCA and continue the trend toward standardization of equipment types used for inspection purposes. The I-2000 has been authorized for inspection use since 2001.

MMCA. The Miniature Multichannel Analyser is a developed miniaturized spectrometry system that supports all detectors used by the IAEA including NaI (called MMCN for this application), CdZnTe (MMCC)

FIG. 3. IMCA shown with an NaI detector and portable computer.

FIG. 4. MMCC: Miniature Multichannel Analyser (MMCA) with CdZnTe detector.

and HpGe (MMCG). The MMCA (Fig. 4) is significantly smaller and lighter than the previous IAEA portable unit, the PMCA, and during operation the battery lifetime is three times longer (at least 12 hours for CdZnTe and NaI detectors). The MMCA has the footprint of a palmtop computer and weighs 680 g, including the lithium ion battery. Combined with a palmtop computer and a CdZnTe detector it makes a powerful yet versatile system that fits into half a briefcase, making it very convenient for many inspection activities.

2.1.4. IAEA high resolution gamma spectrometry techniques

When coupled to a Ge detector, the MMCA or IMCA becomes a high resolution γ ray spectrometer (MMCG or IMCG, Fig. 5). This type of spectrometer is often used to determine the ^{235}U enrichment of uranium hexafluoride (UF_6) in shipping cylinders. When selecting the UF_6 measurement procedure from the options menu in the applications firmware, an inspector is led through a series of predetermined steps to measure and calculate the

FIG. 5. IMCG: Inspector Multichannel Analyser with HpGe detector.

enrichment. The cylinder wall thickness must also be determined so that corrections for γ ray attenuation in the container wall can be made. The thickness is measured with an ultrasonic thickness gauge.

Inspectors can also use the MGAU software which simplifies the measurement and analysis of high resolution uranium spectra. MGAU can provide results with an accuracy of 1–2%, provided that the wall thickness of the steel container is less than 10 mm and that the activity of the thorium daughter is in equilibrium with the parent ^{235}U and ^{238}U activities. The MGAU analysis procedure eliminates the need to measure the container wall thickness or to provide an enrichment calibration for the measurement system.

Another important application of high resolution gamma spectrometry is the determination of the isotopic composition of plutonium. Plutonium emits a complex spectrum of X and γ rays which are interpreted using dedicated software such as MGA and FRAM. These codes take advantage of the high energy resolution of the spectra from a HpGe detector to separate and evaluate the contributions of the different plutonium isotopes. Isotopic determination of plutonium is used to verify the nature of the material and as an input parameter for the interpretation of the neutron measurements. The recently developed TARGA software provides a user friendly environment with the MGA code to determine the isotopic composition of plutonium samples. The combination of the I-2000 system with TARGA software replaces the previously used Medium Count Rate System combined with PUIS software.

2.2. NEUTRON COUNTING

The IAEA uses a number of different types of neutron counting equipment (Table III). This section gives information on the source of the neutrons, the importance of neutron coincidence counting to obtain the mass of fissile fuel, and a few examples of passive and active detector systems.

2.2.1. Neutron emission and detection for non-irradiated fissile fuel

Neutrons are primarily emitted from non-irradiated nuclear fuel in three ways:

(1) Spontaneous fission of uranium and plutonium, particularly involving the even isotopes of plutonium;
(2) Induced fission from fissile isotopes of uranium and plutonium, typically by means of a low energy neutron source;
(3) Alpha particle induced reactions, (α, n) involving light elements such as oxygen and fluorine.

TABLE III. COINCIDENT NEUTRON DETECTOR SYSTEMS FOR NON-IRRADIATED FISSILE FUEL

Code	Equipment name	Primary applications
Passive Neutron Coincidence Counters		
BCNC	Bird Cage Counter	Verification of Pu mass in special storage configurations
CNCM	Compact Neutron Coincidence Counter	Verification (qualitative) of MOX fuel assemblies in shipping crates
DRNC	Drawer Counter	Verification of Pu mass in facility specific containers
FAAS	Fuel Assembly/Capsule Assay System	Verification of Pu mass in MOX fuel assemblies
FPAS	Fuel Pin/Pallet Assay System	Verification of Pu mass in MOX fuel pins in facility specific storage trays
GBAS	Glovebox Assay System	Semiquantitative determination of Pu hold-up in gloveboxes
HBAS	Hold-up Blender Assay System	Semiquantitative determination of Pu hold-up in facility blenders
HLNC	High Level Neutron Coincidence Counter	Verification of Pu in 20–2000 g canned samples (pellets, powders, scrap)
INVS	Inventory Sample Counter	Verification of Pu in 0.1–300 g samples. Modified version can be attached to gloveboxes
LNMC	Large Neutron Multiplicity Counter	Verification of Pu in contaminated/impure items
MAGB	Glovebox Counter	Verification of Pu mass in facility gloveboxes
PCAS	Canister Counter	Verification of Pu mass in MOX canisters
PNCL	Plutonium Neutron Coincidence Collar	Verification of Pu mass in MOX fuel assemblies
PSMC	Plutonium Scrap Multiplicity Counter	Verification of Pu in 1–300 g canned samples of scrap
PWCC	Passive Well Coincidence Counter	Verification of Pu mass in CANDU MOX fuel bundles
UFBC	Universal Fast Breeder Counter	Verification of Pu (up to 16 kg) in FBR fuel
UWCC	Underwater Coincidence Counter	Underwater verification of Pu in fresh MOX fuel assemblies

TABLE III. (cont.)

Code	Equipment name	Primary applications
Active Neutron Coincidence Counters		
AWCC	Active Well Coincidence Counter	Verification of ^{235}U in high enriched U samples
UNCL	Uranium Neutron Coincidence Collar	Verification of ^{235}U in low enriched U fuel assemblies; a variety of collar configurations are available.
WCAS	Waste Crate Assay System	Verification of waste materials
WDAS	Waste Drum Assay System	Interrogation of low level waste drums for Pu mass

Fission neutrons in the first two categories are emitted in groups of two or more per fission event. The multiple neutron signature is detected as a neutron coincidence. Nearly all the isotopes of U, Pu and other transuranic elements emit alpha particles. These interact with light elements present in compounds (e.g. oxides and fluorides) or as impurities (e.g. B, Be and Li) to form an undesirable neutron background. Neutron coincidence counting discriminates against this background by processing neutron pulses to select time correlated (coincident) signatures of multiple neutrons emitted during fission and eliminating the (α, n) neutron pulses that are emitted singly and are thus uncorrelated.

Passive coincidence detector systems determine the mass of Pu based on spontaneous fission primarily in the even numbered isotopes (^{238}Pu, ^{240}Pu and ^{242}Pu, with ^{240}Pu being the dominant contributor). The major fissile isotope, ^{239}Pu, has a typical abundance in fuel of 60% or higher, yet it makes an insignificant contribution to the spontaneous fission neutron signal. Isotopic abundance must be known or verified — typically by means of a high resolution γ ray measurement. Using the isotopic abundance, the ^{240}Pu$_{eff}$ mass determined from coincident neutron count rates can be converted into the total Pu mass for the sample. For uncontaminated, well characterized samples, measurement accuracy can be of the order of 1% or less.

The fissile isotope ^{235}U does not undergo sufficient spontaneous fission for practical passive detection. In this case, an active system incorporating AmLi neutron sources is used to ‘interrogate’ the ^{235}U content through neutron induced fission. For low energy incident neutrons, induced fissions in the ^{238}U of a sample contributes insignificantly to the measured coincident neutron count rate, even though ^{235}U may be enriched to only a few per cent (e.g. low enrichment fuels).

Neutron detectors employ various neutron capture reactions to generate pulses. The reactions produce energetic particles which in turn ionize a gas and produce a charge pulse in response to a neutron interaction. The choice of detector (i.e. the capture material) is based mainly on the neutron detection sensitivity required and on the insensitivity to other radiation, e.g. γ rays. Nearly all detectors are most sensitive to low energy neutrons. Consequently in many neutron measurement systems, detectors are surrounded with a moderator material such as polyethylene to slow energetic neutrons down to thermal energies.

2.2.2. Gross neutron counting

Gross neutron counting refers to the sum of all neutrons detected. Here the neutron source cannot be characterized since coincidence requirements are not applied. The presence of significant numbers of neutrons is often a sufficient indication that fissile nuclear material is present. All the neutron coincidence detection systems (discussed below) determine total neutron count rates as well as coincidence count rates.

Other detector systems, such as the Fork Detector and the Unattended Fuel Flow Monitor, employ gross neutron counting as their primary signature. These systems mainly measure spent fuel materials as described in another section of this booklet.

2.2.3. Neutron coincidence counting

Neutron coincidence counting has evolved into a very stable, reliable and accurate technique for determining Pu and ^{235}U content. Modern, well designed neutron coincidence systems are capable of reliably processing pulses over a very large range of input count rates (i.e. over more than six orders of magnitude). The stability is achieved by judicious selection and placement of amplifier electronics to minimize noise interference. The electronics boards, when located at the detector head, amplify and shape the pulses, apply lower level discrimination to remove γ pulses or noise, and feed out very narrow (50 ns wide) logic pulses to an external pulse processor (the electronics controller).

Reliable coincidence counting is also due to a sophisticated pulse processing circuit (shift register electronics) in the external electronics controller. Pulses occurring within a specified time period (normally set at 64 μs) of one another may be termed correlated (i.e. ‘coincident’) neutron pulses. The correlation time is associated with the slowing down of neutrons in the moderator of the detector head. The shift register electronics circuitry keeps track of coincidences between pulses separated by about 1000 μs (called accidentals) and coincidences in the first 64 μs (called real coincidences plus accidentals). Analysis software provided with a coincidence counter system subtracts the accidentals data from the reals+accidentals data to determine real coincidences. In analysing the information, various small corrections are also automatically applied.

Passive detector systems have two basic geometrical configurations: well detectors that completely enclose the sample or collar detectors that encircle the sample (e.g. a fuel assembly). Well detectors have the preferred geometry since they have the capability to detect all the neutrons emanating from the sample. Collar detectors are an alternative detector design that is appropriate when the sample is too large for placement inside a well detector. Whereas calibrated passive well detectors measure the total mass of Pu in a sample, collar detectors measure Pu mass per unit length of a fuel assembly. The linear density must be multiplied by an effective length to determine the total Pu mass in the assembly.

About twenty versions of passive detector systems are currently used for nuclear safeguards, with design features optimized for specific sample sizes, shapes or Pu mass ranges. The passive detector systems are listed in Table III along with their primary applications. Two representative systems are described below.

HLNC. The High Level Neutron Coincidence Counter is shown in Fig. 6. This detector system is typical of IAEA well detector coincidence counting systems used for measuring non-irradiated Pu materials. The HLNC includes a head which houses the neutron detectors (^{3}He gas proportional counters) connected to special amplifiers. The electronics controller, JSR-12, provides power to the amplifiers and ^{3}He tubes and processes the train of pulses to determine coincidence events. A portable computer connected to the JSR-12 automates the collection of data and analyses and archives the data. A printer, which presents the results in a concise report format, completes the detector package. This 60 kg detector features a large sample cavity and 18% neutron detection efficiency. By removal of the top end cap, a can containing Pu (in pellet, powder or scrap form) can be centred in the large cavity. The sample is given an identification number in the computer, an appropriate calibration curve is selected and a run time (typically 100 s) is designated. Upon initiation of the measurement, the IAEA neutron coincidence counting (INCC) code automatically runs through a sequence of measurements (typically three), each of which must pass all built-in quality control criteria for acceptable results. When the measurements are completed, the Pu mass is calculated and

FIG. 6. *HLNC: High Level Neutron Coincidence Counter.*

compared with the declared value to provide a quantitative verification that for typical high purity Pu inventories is accurate to 1%.

INVS. For small samples (bagged Pu pellets, powders and solutions in vials) with much lower total Pu content than those typically measured with an HLNC, the Inventory Sample Counter (INVS) is the detector system of choice. The INVS has nearly double the neutron detection efficiency of an HLNC. Fig. 7 shows one of four versions of this portable detector system. In another

FIG. 7. *INVS: Inventory Sample Counter.*

version, the INVS has an inverted geometry and is permanently attached to the floor of a glovebox so that samples can be assayed for Pu content without the inconvenience and inefficiency of removing the samples from the glovebox. Although the cavity of an INVS is typically only about 6 cm in diameter by 16 cm high, it is well suited for samples available at facilities such as fuel fabrication plants or on-site laboratories. The INVS provides highly reliable Pu content verification with an accuracy of up to 1% on individual measurements. Measurement procedures are automated with the INCC program and are essentially the same as for the HLNC.

Active detector systems use neutron sources (typically AmLi) to interrogate (induce fission in) the ^{235}U in a sample. A well geometry is again preferred but a collar geometry is needed when the sample is a fuel assembly. The active neutron detectors in use by IAEA safeguards are listed in Table III. Details of an active well detector and an active collar detector are presented below. The full detector system includes a detector head, which detects the neutrons and houses a neutron interrogation source; the electronics controller, which powers the detector and determines the neutron coincidence rates; a portable computer for controlling the measurements and for analysing data to determine ^{235}U content; and the printer for generating reports.

AWCC. The Active Well Coincidence Counter has a large (150 kg) detector head permanently attached to a wheeled cart for transportability (Fig. 8). The AWCC has 42 ^{3}He counters embedded in thick polyethylene cylinders, resulting in a relatively high (nearly 30%) neutron detection

FIG. 8. AWCC: Active Well Coincidence Counter.

efficiency. The ^{235}U content in a sample is interrogated with two AmLi neutron sources placed in the top and bottom end caps to provide a uniform distribution of interrogation neutrons over the sample volume. The cavity size is adjustable up to about 20 cm in diameter and 23 cm in height by removal of inserts and reflectors accommodating samples such as metal disks, canned metal oxide powders and fuel pebbles in carousels. The INCC program is used to automate the measurement procedure and data analysis to enable assaying the ^{235}U content to high accuracy.

UNCL. The Uranium Neutron Coincidence Collar for determining the linear mass density of uranium in fresh fuel assemblies is mounted on a cart. When it is being used at a fuel fabrication or reactor facility, the side containing the neutron source is removed or swung open and the collar is wheeled into position surrounding a fuel assembly. Once the door with the AmLi source is closed, the measurement cycle is initiated. After a specified number of measurements have passed the quality assurance acceptance criteria in the INCC program, the ^{235}U mass per unit length is determined. The linear density data are combined with results of a measurement of the effective length to determine the ^{235}U content of the entire fuel assembly.

2.3. SPENT FUEL MEASUREMENT

2.3.1. Neutron emission and detection

Spontaneous fissions in the ^{242}Cm and ^{244}Cm isotopes are the major source of neutrons emanating from spent fuel. These isotopes are produced through multiple neutron capture events when a fuel assembly is exposed to high neutron fluxes in a nuclear reactor. Fission products in the irradiated fuel produce an extremely high radiation background in which the neutrons must be detected. The high radiation environment influences the type of techniques that can be deployed for spent fuel verification. One approach is to choose a detector which is basically insensitive to γ rays. Another approach is to shield against the γ rays while allowing neutrons to pass through the shield into the neutron detector. Spent fuel verification methods include not only neutron detection but also γ ray and ultraviolet light (Cerenkov radiation) detection.

Table IV lists the spent fuel measurement systems in use by the IAEA. The Fork Detector (FDET) incorporates both neutron and γ ray detectors for gross defect verification of fuel assembly characteristics such as irradiation history, initial fuel content and number of reactor cycles of exposure. Detector systems are available to measure the γ ray energy spectra from irradiated fuel (SFAT and IRAT), and γ ray intensity as a function of fuel bundle storage position (CBVB and

TABLE IV. SPENT FUEL MEASUREMENT SYSTEMS

Code	Equipment name	Description and applications
FDET	Fork Detector Irradiated Fuel Measuring System	Detector system that straddles LWR fuel assemblies with pairs of neutron and γ ray detectors. Gross γ ray and neutron intensities and ratios of intensities can give specific information on the fuel assembly.
SFAT	Spent Fuel Attribute Tester	Gross defect device used for verifying the presence of fission product or activation product at the top of the irradiated fuel assembly.
IRAT	Irradiated Fuel Attribute Tester	Gross defect device used for verifying fission product presence in an irradiated fuel assembly.
ICVD	Cerenkov Viewing Device	Hand-held light intensifying device optimized to view Cerenkov light (near ultraviolet) in a spent fuel storage pond. System can be used in a lighted area. Primarily used to identify irradiated LWR fuel assemblies.
DCVD	Digital Cerenkov Viewing Device	Highly sensitive digital device for viewing Cerenkov light from long cooled, low burnup fuel.
CBVB CBVS	CANDU Bundle Verifier for Baskets CANDU Bundle Verifier for Stacks	Attended radiation monitoring systems that scan storage baskets or stacks of CANDU fuel bundles and record gamma intensity as a function of detector position.
GBUV	Gamma Burnup Verifier	Facility specific system used to make high resolution γ ray measurements of spent fuel assemblies. Collimator in front of the Ge detector is built into the facility.

FIG. 9. FDET: Fork Detector Irradiated Fuel Measuring System (detector head, GRAND electronics unit and portable computer).

CBVS). Cerenkov glow viewing devices (ICVD and eventually a digital device, DCVD) examine the ultraviolet light that appears in the water surrounding spent fuel. The various measurement systems are described in more detail below.

2.3.2. Gross neutron and gamma ray detection

FDET. The Fork Detector Irradiated Fuel Measuring System shown in Fig. 9 includes the detector head, a several metre long extension pipe (not shown), a Gamma Ray and Neutron Detector electronics unit (currently the GRAND3 but eventually to be replaced by the MiniGRAND) and a portable computer. The detector head incorporates γ ray insensitive neutron detectors (four gas filled fission chamber proportional counters) and γ ray detectors suitable for measuring extremely high γ ray intensities (two gas filled ionization chambers). The neutron and γ ray signatures measured by the detectors are used to verify the highly radioactive spent fuel assemblies stored underwater in spent fuel ponds. The FDET is positioned about 1 m above the tops of neighbouring assemblies. The irradiated fuel assembly being measured is lifted so that the tines of the detector straddle the fuel portion of the assembly in order to collect the neutron and gross gamma data.

The ratio of the neutron to γ ray data, when combined with other, complementary information, is used to characterize a particular type of fuel assembly, giving information related to its neutron exposure in the reactor, its initial fissile fuel content and its irradiation history (e.g. the number of cycles for which the assembly was in the reactor).

2.3.3. Gamma ray energy spectral analysis

SFAT. The Spent Fuel Attribute Tester (Fig. 10), consisting of a multichannel analyser electronics unit and a NaI or CdZnTe detector, is used for

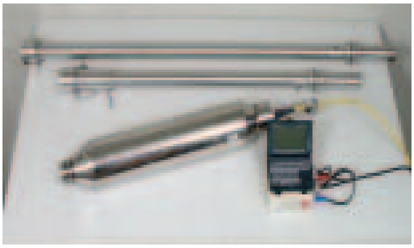


FIG. 10. SFAT: Spent Fuel Attribute Tester.

taking measurements from the top of a fuel assembly as it sits in the storage rack. The SFAT provides a qualitative verification of the presence of spent fuel through detection of particular fission product γ rays — either from ^{137}Cs (662 keV) for fuel that has cooled for longer than four years or from short lived fission products such as ^{144}Pr (2182 keV) for fuel with short cooling times. Activation products such as ^{60}Co are also identifiable. The SFAT is particularly helpful in situations where Cerenkov viewing cannot provide verification, e.g. when Cerenkov radiation is weak because the spent fuel has low burnup and/or a long cooling time, or when water in the storage pond is insufficiently clear. The SFAT and its lead shielding are housed in a stainless steel watertight container which is submerged in a storage pond and positioned over the item to be examined. A watertight collimator pipe is attached below the detector housing to permit only radiation from the principal assembly rather than from adjacent assemblies to reach the detector. A multichannel analyser provides for acquisition, recording and analysis of data, as well as supplying power to the detector. The intensity of the selected γ rays from a specific fuel assembly is compared with the spectrum from the gap separating the assembly from its neighbour to confirm the presence of fission or activation products in the measured assembly.

IRAT. The Irradiated Fuel Attribute Tester (Fig. 11) is a small, lightweight CdZnTe based detector that can be suspended from a spent fuel pond bridge and used to measure a fission product spectrum from a spent fuel assembly partially raised from a storage rack. The detector is housed in a stainless steel cylinder that includes shielding and a collimator. A multichannel analyser collects and analyses spectral information from a spent fuel assembly. The presence of fission product isotopes such as ^{137}Cs, ^{134}Cs, ^{144}Pr, ^{154}Eu and others is used to confirm the irradiated fuel characteristics.

2.3.4. Gamma ray intensity scanning

CBVB, CBVS. The CANDU Bundle Verifier, suspended on an automatic winch whose speed can be set for scanning either storage baskets or storage

FIG. 11. IRAT: Irradiated Fuel Attribute Tester.

stacks, includes a highly collimated and shielded CdTe detector. The verifier is attached to an amplifier and a portable computer. The computer can be used either with an external analyser for high count rate conditions or with an internal multichannel analyser card for moderate count rate applications. The 662 keV γ ray line from ^{137}Cs generally dominates a spectrum for spent fuel that has cooled longer than two years and provides a useful signature for verifying the spent fuel. For shorter cooling times the 757 keV line from ^{95}Nb/^{95}Zr is used to verify the presence of spent fuel. The particular γ ray line to be used is selected in the SCANDU program. The detector head is moved at a selected speed vertically across the face of the stacked fuel and a scan sequence is initiated in the computer. The γ ray intensity is measured as a function of the vertical position. The high intensity peaks, indicating irradiated fuel bundles, are counted and compared with the declared information on the number of stored fuel bundles.

2.3.5. Cerenkov radiation detection

ICVD, DCVD. The Cerenkov Viewing Device (ICVD) and Digital Cerenkov Viewing Device (DCVD) are image intensifier viewing devices sensitive to the ultraviolet radiation in the water surrounding spent fuel assemblies. The hand-held ICVD is shown in Fig. 12. The viewing device is capable of operating with facility lights turned on in the spent fuel pond area. The ICVD is optimized for ultraviolet radiation by filtering away most of the visible light and by having an image intensifier tube primarily sensitive to the ultraviolet light frequencies. Cerenkov radiation is derived from the intense γ radiation emanating from spent fuel, which when absorbed in the water produces high energy recoil electrons. In many cases these electrons exceed the speed of light and therefore must lose energy by emitting radiation (Cerenkov

FIG. 12. ICVD: Cerenkov Viewing Device.

radiation). Spent fuel also emits β particles (which are also energetic electrons), adding to the Cerenkov radiation. Spent fuel assemblies are characterized by Cerenkov glow patterns that are bright in the regions immediately adjacent to the fuel rods. The variation in light intensity is apparent when viewed from a position aligned directly above the fuel rods. With careful alignment and appropriate assessment of the object being viewed, an irradiated fuel assembly can be distinguished from a non-fuel item that may look the same to the naked eye. Typically, a row of fuel assemblies is viewed vertically from the bridge while the facility operator slowly runs the bridge down the row. One inspector views the items in the row through the ICVD and verbally declares each item as spent fuel, as a void or as some other object, while a second inspector compares the observed results with the facility declarations. The DCVD is currently being developed for use in verifying assembles with long cooling times and/or low burnups which have weak Cerenkov signals that cannot be seen with a standard ICVD.

2.4. OTHER NDA TECHNIQUES

2.4.1. Radiation measurement

KEDG. The K-edge Densitometer is facility owned equipment used by the IAEA to determine the Pu concentration in solutions. The system consists of a high resolution Ge detector, a multichannel analyser and a portable computer. A ^{57}Se/^{57}Co source of low energy γ rays is positioned to permit the γ radiation to pass through a small sample vial of the solution. Determination of the amount of absorption of this radiation provides a highly sensitive measure of the concentration of Pu in the sample.

FIG. 13. LCBS: Load Cell Based Weighing System.

2.4.2. Physical property measurement

The IAEA also uses equipment to measure such quantities as the weight of an object (LCBS), the wall thickness of a container (ULTG) and the liquid level in a tank (PTMS).

LCBS. The Load Cell Based Weighing System, shown in Fig. 13, operates in two load ranges up to 5000 and 20 000 kg and provides a convenient and rapid means of determining the gross weight of bulky, massive objects such as UF_6 shipping cylinders. The load cell construction includes two shackles separated by a load supporting element that is bonded to a strain gauge. When a load is lifted with the hoist, the strain gauge deforms, changing its electrical resistance. The resistance change is converted into a weight displayed on a digital readout unit that is attached through a cable to the load cell. Typically, gross weights are determined with this system to an accuracy of better than 1%.

FIG. 14. ULTG: Ultrasonic Thickness Gauge.

ULTG. The Ultrasonic Thickness Gauge (Fig. 14) is a small hand-held device with a digital readout that measures the wall thickness of an object based on the round trip flight time of ultrasonic waves that are reflected from the inner wall. The thickness information is sometimes needed to adjust for radiation attenuation in walls of containers such as UF_6 shipping containers, UO_2 hoppers and UO_2 cans. These corrections are particularly important when container wall thicknesses vary. Using the ULTG standard probe, the typical measurement range for steel extends from 1.2 to 200 mm. In the standard mode of operation, the speed of the ultrasonic waves in a particular medium is stored in the memory of the ULTG, so that the flight time can be internally converted directly into a wall thickness and displayed on the readout.

3. DESTRUCTIVE ANALYSIS

Destructive analysis (DA) measurements for element assay and determination of isotopic composition can be made on all types of solid and liquid materials encountered in bulk handling nuclear plants. DA is used in the following ways:

(a) To verify that protracted diversion of safeguarded nuclear materials has not occurred,
(b) To certify working standards used for the calibration of NDA and installed verification instruments,
(c) To provide assurance of the quality and independence of on-site measurements (e.g. validation of facility specific procedures),
(d) To carry out periodic verifications of the operator's measurement system.

DA verification measurements involve the following steps:

(1) The taking of independent samples;
(2) Their conditioning at the facility to ensure that they are in a chemical form adequate for maintaining their integrity during transport;
(3) Their packaging, sealing and shipment to the IAEA Safeguards Analytical Laboratory (SAL) in Seibersdorf, near Vienna;
(4) Their analysis by SAL or the Network of Analytical Laboratories (NWAL), consisting of laboratories in different States that have been certified to analyse safeguards relevant samples;
(5) The statistical evaluation of the results of their analysis.

To obtain meaningful and sufficiently accurate results, it is necessary to apply optimized and validated procedures for each of these steps.

Bulk measurement is generally considered to be part of sampling. The sample related bulk data collected on-site by the inspector concomitantly with the sampling include the weights or volumes of the sampled items or batches as declared by the operator and verified by the inspector. In addition to the bulk data, the operator's declarations for the elemental and isotopic compositions of the material sampled are recorded in a working paper. This working paper provides instructions for the sample amounts to be taken and the most appropriate sample bottle to be used. Specific types of sample bottle have been selected and tested by the IAEA for taking and shipping samples of various types of materials (Fig. 15).

The main analytical techniques applied in DA measurements are summarized in Table V. The measurement precisions and accuracies reflected in

FIG. 15. Sample bottles used for IAEA verification samples. Top left: vials for Pu, MOX or high enriched U powder. Top right: hard polyethylene bottle for hard or solid materials. Bottom left: glass bottle for depleted, natural or low enriched U powder. Bottom right: UF_6 *container.*

the table by the random and systematic uncertainties, respectively, are values achieved in the analysis of materials of nuclear grade or similar chemical purity. They include the contributions of all uncertainties occurring after sampling. The effects of sampling, impurities and foreign components will vary with the type of material, to the extent that sampling uncertainties can become the dominant factor in the total measurement error.

3.1. ELEMENTAL ANALYSIS

3.1.1. Uranium by potentiometric titration

The New Brunswick Laboratory Davies and Gray titration is the basic method for the determination of U content in gram size samples of all types of non-irradiated materials. An automated titration system (Fig. 16), developed at

TABLE V. MAIN ANALYTICAL TECHNIQUES USED BY THE SAL AND THE NWAL

Analytical technique	Analysed for	Type of material	Uncertainty (% rel.) Random	Uncertainty (% rel.) Systematic
Elemental analysis				
NBL Davies and Gray titration	U	U, U–Pu, U–Th[a]	0.05	0.05
MacDonald and Savage titration	Pu	Pu materials[a]	0.1	0.1
Controlled potential coulometry	Pu	Pure Pu materials	0.1	0.1
Ignition gravimetry	U, Pu	U oxides	0.05	0.05
K-edge X ray densitometry	U, Th, Pu	U, Pu, U–Pu, U–Th[a]	0.2	0.2
K X ray fluorescence analysis	Pu	Pu materials[a]	0.2	0.2
Wavelength dispersive X ray fluorescence spectrometry	Pu, U	Pure U and Pu oxides, and MOX[a]	0.3	0.3
Isotopic dilution mass spectrometry	U, Pu	Spent fuel input solutions, Pu and U–Pu materials, HALW	0.1	0.1
Plutonium (VI) spectrophotometry	Pu	Pu, U–Pu[a]	0.2	0.2
Alpha spectrometry	Np, AM, CM	HAWL, Spent fuel input	5.0	5.0
Isotopic analysis				
Thermal ionization mass spectrometry	U and Pu isotopes	All Pu and U materials, and spent fuel input solutions	0.05[b]	0.05[b]
High resolution γ ray spectrometry (Ge detector)	Pu isotopes, Am, Np	Pure U and Pu materials	0.5–2.0	0.5–2.0
Gamma ray spectrometry (NaI detector)	^{235}U	Low enriched U materials	0.2–0.5	0.2–0.5
Alpha spectrometry	^{238}Pu	Pu materials	0.2	0.3

[a] Except spent fuel.

[b] For ratios of major isotopes.

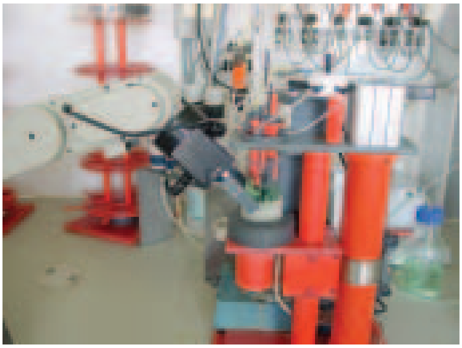


FIG. 16. Automatic U titrator.

SAL, achieves measurement precisions and accuracies of 0.05%rel. or better in routine operation. This method is applicable to samples of any U materials containing at least 50 mg U so that at least four replicate aliquots of the sample, containing at least 10 mg U each, can be titrated.

3.1.2. Plutonium by potentiometric titration

The MacDonald and Savage titration is used for the determination of Pu content in gram size samples of non-irradiated nuclear materials. It provides precisions and accuracies of 0.1%rel. or better. This method has been designed to determine 2–4 mg Pu in nitric acid solutions. It is suitable for the direct determination of Pu in nuclear materials ranging from Pu from a reprocessing plant to fresh reactor fuel materials with a U:Pu ratio of up to 30.

3.1.3. Plutonium by controlled potential coulometry

Controlled potential coulometry (Fig. 17) is used to determine 4–10 mg Pu. Coulometry can also be used to determine Pu in samples of industrial materials, provided that chemical separation is first carried out to remove potential interfering elements. The technique applies to gram size Pu samples, such as Pu product solutions, Pu metal and Pu oxide powders or pellets, and to mixed U and Pu oxides after dissolution of the solid sample.

3.1.4. Uranium by ignition gravimetry

Ignition gravimetry is applied for determining U concentrations in nuclear grade U and Pu oxides. An accurately weighed sample is converted to stoichiometric U_3O_8 by ignition in air to a constant mass at 900°C ± 10°C for U.

FIG. 17. Coulometry cell for determination of Pu concentration.

The amount of U or Pu in the sample is calculated using a gravimetric conversion factor for U_3O_8 to U, depending on the isotopic composition of the sample. The precision and accuracy for nuclear grade oxides containing less than 200 ppm of impurities are of the order of 0.05%rel. or better.

The presence of non-volatile impurities (the more frequent and abundant being Fe, Si, Al and Ca) requires a correction, based on the impurity content determined by X ray fluorescence spectrometry and/or inductively coupled plasma–mass spectrometry.

3.1.5. Uranium, thorium or plutonium by K-edge X ray densitometry

K-edge X ray densitometry (or hybrid K-edge densitometry, HKED) is applicable to all U, Th and Pu materials and to mixed U–Th or U–Pu samples containing a sufficient amount of the analyte: a precision and accuracy of about 0.2%rel. may be achieved when the concentration of the analyte ranges from 50 to 150 g/L. The method is very selective.

3.1.6. Plutonium by K X ray fluorescence analysis

K X ray fluorescence analysis is applied to samples of PuO_2 and Pu nitrate solutions containing at least 3–4 mg Pu with the addition of known amounts of

FIG. 18. Uranium/plutonium by K-edge X ray densitometry (HKED).

U as an internal standard. It is also used for U assay in samples of MOX with a determination of the Pu content by titration. A precision and accuracy of 0.2%rel. are achievable.

3.1.7. Plutonium and/or uranium by wavelength dispersive X ray fluorescence spectrometry

X ray fluorescence spectrometry is used in conjunction with a commercial high frequency furnace for fast analysis of Pu and mixed U–Pu oxides (Fig. 19). About 0.3 g of the sample is melted in a lithium borate flux and the melt cast into a platinum dish, producing a borate disk of very homogeneous composition. The concentrations of Th, U, Np, Pu and Am can be determined simultaneously by measuring the fluorescence of the L_a lines. The calibration

FIG. 19. X ray fluorescence spectrometer.

curves are linear over at least a tenfold change in concentration. A complete analysis can be performed in about 15 min, with a reproducibility of about 0.3% for the concentrations of the major heavy elements.

X ray fluorescence spectrometry is also used to determine, semi-quantitatively in various types of samples, the concentrations of major, minor and trace elements with atomic masses from 9 (fluorine) through to 89–103 (the actinide elements).

3.1.8. Uranium or plutonium by isotope dilution mass spectrometry

Isotope dilution mass spectrometry is applied for U or Pu determinations in all samples of spent fuel input solutions, but also for samples of low content, such as milligram size U–Pu samples and wastes.

For U and/or Pu determinations in high burnup spent fuel input solutions, an aliquot of the sample solution is spiked with a known amount of a certified tracer containing enriched ^{235}U and ^{239}Pu. For pure U materials, a spike of ^{233}U is used; for pure Pu materials or low burnup spent fuel, a spike of ^{242}Pu or ^{244}Pu is used. Spiked solutions of Pu bearing materials are chemically treated to attain an isotopic equilibrium of Pu. Two spiked aliquots and an unspiked aliquot are separately purified by chromatography in order to provide pure fractions for thermal ionization mass spectrometry (see Section 3.2.1.). The chemical treatment of spent fuel samples is performed with a fully automatic, robotized system (Fig. 20). The resulting U and Pu fractions are then

FIG. 20. Robotized system for separation of spent fuel input solution samples.

evaporated to dryness and redissolved in nitric acid to yield solutions containing about 1 μg U and 50 ng Pu per microlitre. The isotopic ratios of both the spiked and unspiked aliquots are measured by thermal ionization mass spectrometry and the U and Pu contents are calculated accordingly. When the original sample can be spiked directly and total evaporation mass spectrometry measurements are done, the elemental assays have a precision and accuracy of 0.1%rel. or better.

3.2. ISOTOPIC ANALYSIS

3.2.1. Uranium or plutonium isotopic composition by thermal ionization mass spectrometry

Thermal ionization mass spectrometry, employing three multidetector mass spectrometers, each equipped with nine Faraday cups, is used to measure the U or Pu isotopic composition of all samples of nuclear materials submitted to SAL (Fig. 21). Comprehensive new software, developed in co-operation with the Institute of Reference Materials and Measurements in Geel, Belgium, the Los Alamos National Laboratory in the United States of America and SAL, includes routines for basic calibration steps, such as the cup linearity test, relative cup efficiency measurements and a system calibration of mass fractionation effects.

Isotope ratios of 0.05–20 can be measured with a precision and accuracy of 0.05%rel. using a data collection procedure involving total evaporation of the sample loaded on the filament. This procedure greatly reduces the mass fractionation effects.

FIG. 21. Thermal ionization mass spectrometer.

3.2.2. Plutonium isotopic composition by high resolution γ ray spectrometry

High resolution γ ray spectrometry is used to screen all Pu samples as they are received at SAL. The Pu content of samples containing Np is analysed by isotope dilution mass spectrometry rather than by potentiometric titration. SAL has thereby acquired considerable experience in isotopic analyses using a multipurpose γ ray spectrometry analysis program called MGA (Multi-Group Analysis).

Samples containing Pu are placed, in their original packaging, on a planar Ge detector and a spectrum is acquired in the energy range 0–614 keV. The spectrum is then analysed using MGA, which calculates the abundances of ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu. The isotope ^{242}Pu is estimated from isotopic correlation. The abundances of ^{235}U and ^{237}Np, if present in the Pu sample, as well as that of ^{241}Am, are determined simultaneously. Typical precisions and accuracies range between 0.5 and 2%rel. for all isotope abundances except ^{242}Pu.

3.2.3. Uranium-235 in solution by γ ray spectrometry

Gamma ray spectrometry with a NaI detector is used as a backup procedure for mass spectrometry in the determination of ^{235}U enrichment of U samples, which are dissolved and analysed for U concentration by potentiometric titration.

In this procedure, 5 mL aliquots of a U solution containing about 80 g/L U in 1M nitric acid are weighed into identically shaped glass tubes and the tubes closed with a stopper. A set of five standard solutions, containing known concentrations of NBS standards (U-010, U-015, U-020A, U-030A and U-050) is used for calibration. The number of counts at the 185.7 keV energy peak of ^{235}U is calculated and related, in weight per cent, to the total U content of the sample which has been assayed by titration. In the absence of radioisotope interferences, the results have a precision and accuracy ranging between 0.5%rel. for natural and 0.2%rel. for enriched U.

3.3. OTHER DA TECHNIQUES

Alpha spectrometry is applied for the measurement of ^{238}Pu abundance with Si (Li) or ion implanted detectors. This method is used in parallel with isotope dilution mass spectrometry for the determination of ^{238}Pu abundance or for the measurement of Pu in spent fuel samples. Neptunium-237 (^{241}Am) and ^{244}Cm are also measured by alpha spectrometry in combination with chemical separations. ^{237}Np (^{241}Am) and ^{244}Cm are also measured by alpha spectrometry in combination with chemical separations.

Plutonium(VI) spectrophotometry is applicable to the determination of milligram amounts of Pu in small samples of products, with accuracies similar to those of titration.

Inductively Coupled Mass Spectrometry (ICP/MS) can determine most elements at the parts per billion (ppb) level in solution. It is used for the quantitative and qualitative determination of impurities in various matrices (including many inspection sample types).

4. CONTAINMENT AND SURVEILLANCE

Containment and surveillance techniques are extensively used by the IAEA because they are flexible and cost effective. The two main C/S categories are optical surveillance and sealing systems.

Optical surveillance is most effective in storage areas (such as spent fuel storage ponds) with relatively few activities that could be interpreted as the removal of nuclear material. A typical application would consist of two or more cameras positioned to completely cover the storage area. The field of view of the cameras is such that any movement of items that could be the removal of nuclear material is easily identified. This means that items have to be sufficiently large within the field of view to be identified and that one or more images have to be recorded during the movement of material. The image recording may be set at a periodic frequency (significantly shorter than the fastest possible removal time) or the motion (i.e. scene change) may trigger the recording. Optical surveillance is intrinsically an unattended operation that may be enhanced by the remote transmission of image data or system operation data (i.e. the status of the surveillance system). Unattended and remote monitoring systems are discussed in Section 5.

Seals are typically applied to individual items containing nuclear material. A seal can help to indicate that material was neither introduced into or removed from a container. At the same time, sealing provides a unique identity for the sealed container. Unattended IAEA monitoring equipment is also sealed. Most IAEA seals are applied for extended periods of time, typically several months to years. Seals may be either single use seals that are replaced when checked or seals that are verifiable in situ, i.e. they can be checked for integrity and identity in the field. If the seals are verifiable in situ then the verification activity must be efficient (to limit radiation exposure to the inspector) and extremely reliable. The in situ verification activity must consist of checking the item containment, the seal integrity and the method of the seal's attachment to the item.

4.1. SURVEILLANCE

Surveillance includes both human and instrument observation. Because it is prohibitively expensive to provide round-the-clock human surveillance, the IAEA has developed a range of optical surveillance systems that can provide effective, ongoing surveillance when an inspector is not physically present on-site. Unattended optical surveillance techniques are used widely by the IAEA to support and complement nuclear material accountancy and to provide continuity of knowledge about nuclear materials and other items of safeguards significance between on-site inspection visits.

Effective surveillance is achieved when a camera's field of view covers the entire area of safeguards interest to capture the movement of safeguarded items. Additionally, the picture taking interval is set to record at least two images, should the item be moved, so that its direction of movement can be determined. The image recording frequency may be set at a fixed time interval, which is significantly shorter that the fastest removal time, or may be triggered by scene change detection or other external triggers.

Optical surveillance is intrinsically an unattended technique that can be used to record images only, or it may be integrated with other unattended monitoring equipment to provide nuclear measurement, containment history and other data. The IAEA's surveillance systems can also automatically transfer data to IAEA Headquarters or to an IAEA regional office.

Surveillance equipment is designed to meet several basic application requirements. Chiefly, those requirements are as follows:

(a) Single camera — for easy to access locations,
(b) Single camera — for difficult to access locations,
(c) Multi-camera — for larger and more complex facilities,
(d) Short term surveillance — for activities that include open core monitoring,
(e) Surveillance — for remote monitoring,
(f) Underwater closed circuit TV — for attended applications in fuel storage ponds.

IAEA surveillance equipment has evolved from film cameras, through systems based on videotape technology, to today's digital image surveillance (DIS) systems. The evolution of IAEA surveillance equipment has been mandated mostly by strong commercial trends that dictate the availability of applicable technologies on the market. With a significant reduction in the number of moving parts, DIS is inherently more reliable than previous film and videotape technologies. Other benefits include enhanced digital data evaluation, assisted review capabilities, improved authentication and encryption and its facilitation of remote monitoring.

In 1995, the IAEA embarked upon a replacement programme to phase out old and obsolete surveillance equipment. In 1998, the Department of Safeguards decided that surveillance systems based on the DCM14 digital camera module (Fig. 22) most closely met the essential user requirements for the IAEA surveillance systems and that they were the most suitable equipment for the replacement of the existing film and videotape based systems. While

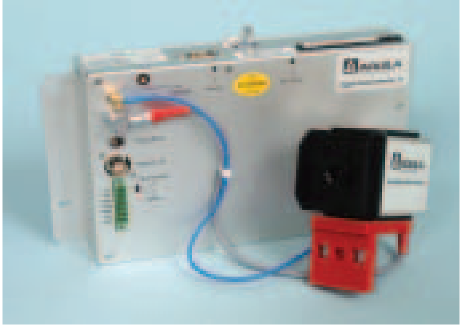


FIG. 22. DCM14 with video CCD camera (CCD: Charge Coupled Device).

very compact, the DCM14 performs many tasks required for a safeguards surveillance system, including:

(1) Digitization of a standard video camera image;
(2) Image and data authentication, ensuring genuineness;
(3) Image and data encryption, ensuring confidentiality;
(4) Image compression to reduce image and data storage requirements;
(5) Local storage to ensure redundancy when data are transmitted out of the camera housing;
(6) Detection of changes in the camera's field of view (scene change detection);
(7) Power management to ensure maximum possible operation should the local facility's power fail;
(8) Secure remote surveillance when connected to a communications server.

Safeguards surveillance systems are relatively unique in that the equipment must operate unattended for extended periods in harsh conditions and with a high degree of security. Despite repeated attempts over the years to identify commercial off-the-shelf equivalents, no immediately applicable systems were found. Systems that nearly meet the requirements invariably require some degree of modification, entailing additional costs.

Because of its inherent flexibility, the introduction of the DCM14 also provided a means to consolidate and standardize future surveillance systems. Using the DCM14 in different configurations it became possible to assemble single and multiple camera systems for easy and difficult to access locations from a standard array of basic building blocks. Since 1998, the DCM14 has been used to construct 5 basic digital surveillance systems, meeting the full range of safeguards applications, often in difficult environments. The replacement strategy is summarized in Table VI.

TABLE VI. REPLACEMENT AND CONSOLIDATION PLAN FOR SURVEILLANCE SYSTEMS

Application	Film, videotape and early digital systems currently in use, but to be phased out (1995–2002)		DIS and other systems in current and future use (2003–)	
Installed Single-Camera *-for easy to access locations*	CSMS	Compact Surveillance and Monitoring System (COSMOS)	ALIS	All in one surveillance, mains operated
	PHSR	Photo Surveillance Unit (Minolta)	ALIP	All in one surveillance, portable battery operated
Installed Single-Camera *-for difficult to access locations*	GDTV	Gemini Digital Video System	DSOS	Digital single-camera optical surveillance
	MIVS	Modular Integrated Video System		
Installed Multi-Camera	MXTV	Multiplex TV Surveillance System	SDIS	Server digital image surveillance Up to 6 cameras
	MOSS	Multi-Camera Optical Surveillance System	DMOS	Digital Multi-Camera Optical Surveillance Between 6 and 16 cameras
	UEMS	Upgraded Euratom Multi-Camera Optical Surveillance System (EMOSS)	FAST	FAST company surveillance system *Developed by Euratom for joint inspection use*
	VSEU	Video System Multiplex (DigiQuad)		
Short Term Surveillance	STVS	Short Term TV System	ALIP	All in one surveillance portable
Surveillance for Remote Monitoring			SDIS	Server digital image surveillance

TABLE VI. (cont.)

Application	Film, videotape and early digital systems currently in use, but to be phased out (1995–2002)		DIS and other systems in current and future use (2003–)	
			DMOS	Digital multi-camera optical surveillance
Underwater TV *-for attended applications*	UWTV UWVD	Underwater TV Underwater Viewing Device	UWTV UWVD	Underwater TV Underwater viewing device
Surveillance Review *- hardware and software*	GARS 6.3 MARS MORE	General Advanced Review Station Version 6.3 MIVS Advanced Review Station Multi-system Optical Review Station	GARS 6.4	General Advanced Review Station Version 6.4

Surveillance continues to play an important role in safeguards. Over the past few years there has been a steady increase in the number of camera units deployed in safeguarded facilities.

Currently, the IAEA maintains about 800 cameras connected to 400 surveillance systems in 170 safeguarded sites worldwide. While replacement of the older systems is well under way, the programme is not expected to be fully completed before 2005. Until that time, old and new systems will continue to coexist. Table VII provides an overview of the IAEA's main systems for the coming years.

Equipment has also been developed to provide an increasingly sophisticated review capability for surveillance. Following the same technology trends, review stations have evolved from film review tables, through videotape systems (some with advanced features such as scene change detection) to the IAEA's most recent GARS review software that can be run on a personal computer equipped with the appropriate digital media peripherals. Further details of the IAEA's new and most widely used digital surveillance systems follow.

TABLE VII. OPTICAL SURVEILLANCE SYSTEMS

Code	Equipment name	Description and applications
Photographic system		
PHSR	Photo Surveillance Unit (Minolta)	Battery powered, twin and triple Minolta film cameras used for general and short term surveillance. Phased out.
Videotape: single camera surveillance systems		
CSMS	Compact Surveillance and Monitoring System (COSMOS)	Battery or mains powered, self-contained single camera surveillance system for easy to access locations. Phased out.
MIVS	Modular Integrated Video System	Single camera surveillance systems for difficult to access locations. Phased out.
SIDS	Sample Identification System	Facility specific surveillance system integrated with an HLNC and triggered by neutrons above a pre-set threshold, allowing MOX sample identification in a fuel fabrication facility.
STVS	Short Term TV System	Single camera and recorder, developed from MXTV equipment, for short term surveillance applications. To be replaced by ALIS and ALIP.
UWTV	Underwater TV	Commercial underwater closed circuit TV system (CCTV) for inspector attended fuel ID verification in storage ponds.
Digital: single camera surveillance systems		
ALIP	All In One Surveillance Portable	Battery powered, single camera for easy to access locations or for portable surveillance applications.
ALIS	All In One Surveillance	Mains powered, single camera for installation in easy to access locations
DSOS	Digital Single-Camera Optical Surveillance	Single camera for installation in difficult to access locations.
GDTV	Gemini Digital Video System	Early single camera, digital surveillance system for difficult to access locations. A replacement for CSMS and MIVS. To have been phased out by early 2003.

TABLE VII. (cont.)

Code	Equipment name	Description and applications
Videotape: Multi-camera surveillance systems		
FTPV	Fuel Transfer Video	Facility specific CCTV system used at fuel transfer ponds.
MOSS	Multi-Camera Optical Surveillance System	Videotape based, multiple camera surveillance system for up to 16 cameras. To be phased out by 2005/2006.
MXTV	Multiplex TV Surveillance System	Videotape based, multiple camera surveillance system for up 16 cameras. To be phased out by 2004/2005.
VSEU	Video System Multiplex (DigiQuad)	Dual use surveillance systems developed by Euratom.
VSPC	Video system	Facility specific CCTV system for up to 4 cameras on a split display screen.
Digital: Multi-camera surveillance systems		
DMOS	Digital Multi-Camera Optical Surveillance	Multiple camera surveillance system for up to 16 cameras with remote monitoring capability.
SDIS	Server Digital Image Surveillance	Multiple camera surveillance system for up to 6 cameras with remote monitoring capability.
UEMS	Upgraded Euratom Multi-Camera Optical Surveillance System	Upgraded EMOSS system for up to 4 cameras. To be phased out by 2004.
Surveillance review systems		
GARS	General Advanced Review Station Software	For the review of ALIS, ALIP, DMOS, DSOS, GDTV, SDIS surveillance.
MARS	MIVS Advanced Review Station	For MIVS surveillance only Phased out.
MORE	Multi-system Optical Review Station	For COSMOS, MIVS, MXTV, MOSS, VSEU. To be phased out by end 2005.

FIG. 23. ALIS: All In One Surveillance Unit.

4.1.1. Installed single camera for easy to access locations

ALIS. The All In One Surveillance Unit (Fig. 23) is a mains operated, fully self-contained digital surveillance system based on the DCM14 digital camera module. All the components fit within a standard IAEA camera enclosure with all the functionality of the DCM14 plus an intergraded inspector interface terminal. Images and associated log files are stored on PCMCIA flashcards. With a 660 Mbyte flashcard installed, ALIS can record between 40 000 and 50 000 images, depending on the compression used.

4.1.2. Installed single camera for difficult to access locations

DSOS. The Digital Single Camera Optical Surveillance System (Fig. 24) is based on DCM14 technology and is designed for applications where the camera must be placed in a difficult to access location. DSOS consists of a DCM14 based digital camera connected to a recording unit by a special

FIG. 24. DSOS: Digital Single Camera Optical Surveillance System.

composite cable. The recording unit, which is also based on DCM14 technology, allows an inspector to service the system at a more convenient and safe location using procedures similar to those used when servicing an ALIS. DSOS may also be used as a direct replacement for MIVS.

4.1.3. Installed multi-camera

SDIS. The Server based Digital Surveillance System (Fig. 25) was initially developed for remote monitoring applications. Its primary function is the collection of images and data from up to 6 DCM14 surveillance cameras. It may also be used for the direct interrogation of VACOSS seals. The SDIS server sorts and classifies image and other data and can securely transfer images and data to IAEA offices. An uninterrupted power supply unit is an integral part of SDIS and has been designed to keep the system in full operation for about 48 hours without an external mains power supply. Figure 25 shows the internal parts of SDIS.

Two modes of operation are available:

(1) Unattended: The data are stored on a removable Jaz disk and are physically carried to the GARS equipped review station.
(2) Remote monitoring: The data are transferred to an IAEA office by telephone line (PSTN), ISDN, ADSL, frame relay or satellite link and subsequently reviewed on a GARS equipped review station.

DMOS. The Digital Multi-Camera Optical Surveillance (Fig. 27) is designed for unattended and remote monitoring applications. DMOS is used for applications requiring between 6 and 16 cameras connected to a central recording and communications console. DMOS is based on DCM14 technology and as with the SDIS each camera is interrogated by a server computer. Images

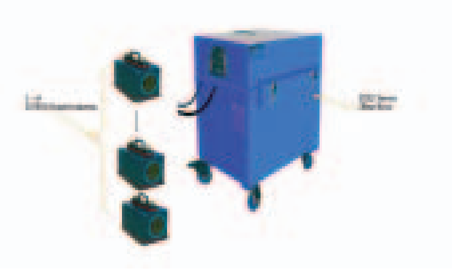


FIG. 25. SDIS: Server based Digital Surveillance System.

FIG. 26. SDIS server ('blue box' — lid open).

and data from each camera are initially stored on a large RAID array prior to final storage on a removable digital linear tape (DLT).

4.1.4. Short term surveillance

ALIP. The All In One Surveillance Portable Battery Unit (Fig. 28) is a battery operated, fully self-contained digital surveillance system based on the

FIG. 27. DMOS: Digital Multi-Camera Optical Surveillance.

FIG. 28. ALIP: All In One Surveillance Portable Battery Unit.

DCM14 digital camera module. It consists of a camera, a video terminal, the DCM14 digital camera module, a mains operated power supply and a set of batteries, all of which are enclosed in a camera housing that has the same footprint as the standard IAEA camera housing but has been extended vertically to accommodate the batteries. With fully charged batteries, the system can perform surveillance duties for up to 100 days with no external power. Images and associated log files are stored on PC cards. With a 660 Mbyte flashcard installed, ALIP can record between 40 000 and 50 000 images, depending on the compression used.

4.1.5. Underwater TV for attended applications

The portable UWTV system (Fig. 29) is mainly used for verifying bundles in spent fuel ponds of CANDU type reactors. It can also be used for all other

FIG. 29. UWTV system.

kinds of underwater inspections. A complete system consists of a radiation hardened camera, a camera control unit (CCU) and various accessories such as a motorized 90 degree rotating head and a light system. Light accessories are available for long and short distance verification activities. For bundle ID verifications, the camera must be capable of reading small letters under limited light conditions and withstand a very high level of radiation, still remaining watertight down to a depth of 15 metres in water. The CCU has a built-in monochrome monitor for on-site review. The video can also be recorded on an external videocassette recorder.

4.1.6. Surveillance review software

MORE. The Multi-System Optical Review Station (Fig. 30) was designed to assist inspector review of CSMS, MIVS, MXTV and MOSS videotapes. With the phasing out of CSMS and MIVS in 2002, MORE will continue to be used for the review of MXTV and MOSS until those surveillance systems in the field can be replaced by digital multi-camera equivalents (e.g. DMOS).

Each MORE system comprises an IBM compatible computer running MORE software (with a built-in DAT drive to archive digitized images), a display unit for the computer, a monochrome video monitor with automatic CCIR/EIA-170 video standard detection, three videotape recorders to replay surveillance tapes and a printer for reports. To utilize the scene change detection option it is first necessary to create set-up files. Regions of interest are defined within the recorded image captured by the camera in the field. Regions of interest are defined in the field of view as areas of safeguards significance (e.g. possible paths for the removal of safeguarded material).

FIG. 30. MORE: Multi-System Optical Review Station.

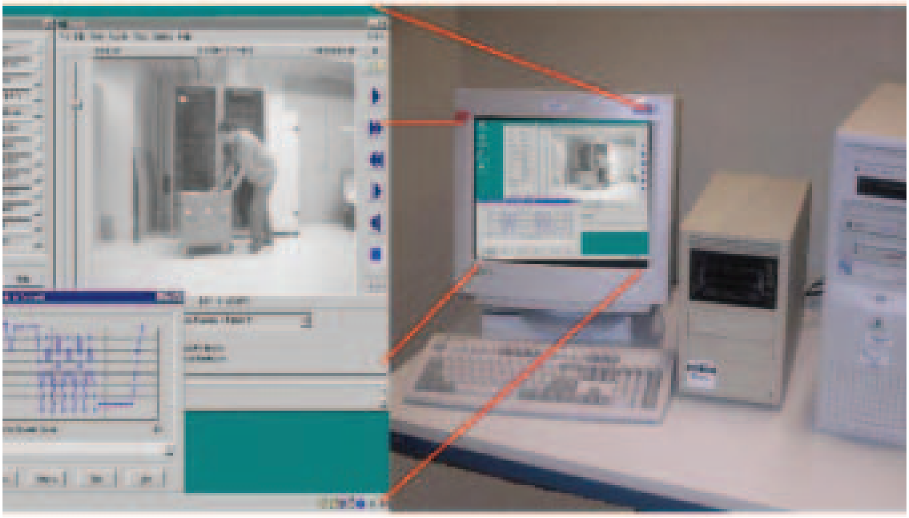


FIG. 31. GARS software.

GARS. The General Advanced Review Station software (Fig. 31) was developed to run on a personal computer with the appropriate media drives to review the recorded images from ALIP, ALIS, DSOS, DMOS, GDTV and SDIS.

At its simplest, GARS provides a flexible and user friendly inspector interface (similar to popular commercial media players) for the review of images and data from flashcards, Jaz disks, removable hard drives, CD-ROMS and DLTs. GARS also has advanced features that can be used to reduce an inspector's review effort. Those features include image and data authentication verification, image and data decryption, scene change detection of recorded images, digital image enhancement and multiple camera display options.

4.1.7. Miscellaneous surveillance systems and options

In addition to the systems described above, new surveillance systems and equipment to enhance the capabilities of existing surveillance equipment are both under development and under evaluation. Table VIII summarizes those systems.

4.2. SEALS

Seals, sometimes referred to as tamper indicating devices, are used to secure materials, documents or any other important items in a tamper-proof

TABLE VIII. OPTICAL SURVEILLANCE SYSTEMS

Code	Equipment name	Description and applications
FAST	FAST company surveillance system	Multiple camera digital surveillance system, developed by Euratom for joint use applications. Under evaluation.
LRFO	Laser Range Finder Option	Option for the attachment of DCM14 based cameras to counter in-front-of-lens tampering. Under development.
VMOS	VACOSS-S/MOSS System	Option that allows the integration of the MOSS multi-camera surveillance system with a remotely verifiable VACOSS seal. To be phased out with MOSS.
WCSS	Wall Containment Sensor System	Wall penetration detection for triggering surveillance images. Under evaluation.

containment. The purpose of the seals is to provide evidence of any unauthorized attempt to gain access to the secured material. The seals also provide a means of uniquely identifying the secured containers. Depending on the type of application, several seals are in use by Operations Divisions as shown in Table IX. It must, however, be pointed out that the seals do not provide any kind of physical protection, nor were they designed to provide such protection.

4.2.1. Single use seals

CAPS. The Metallic Seal is extensively used for sealing material containers, material cabinets and IAEA safeguards equipment. Typically, 20 000 of these metal cap seals are verified each year. The seal is detached in the field and brought to IAEA Headquarters for identification. The primary advantages of CAPS are that it is simple, inexpensive and easily attached or detached by the inspector. Attachment and detachment efficiency is important to limit the radiation exposure of the inspector. Unique identification of each seal is obtained by imaging random scratches on the inside surface of the metal cap and by comparing the installation and removal images (Fig. 32).

FIG. 32. Comparison of metal cap seal images for seal validation.

VOID. The Improved Adhesive Seal is made of special material which cannot be detached without being destroyed. The seal breaks along special slots cut into the material in a way that does not enable the seal to be reattached. As for all adhesive seals, the seal is intended only for temporary applications (24 hours or less).

4.2.2. In situ verifiable seals

In situ verifiable seals are a kind of seal that is uniquely identifiable and verifiable in the field. They fall into the three main categories of fibre optic, ultrasonic and electronic seals.

FBOS. In the Fibre Optic General Purpose Seal the seal wire as used in CAPS is replaced by a multi-strand plastic fibre optic loop with its ends enclosed in a seal in such a way that a unique random pattern of fibres is formed. This can be verified by shining a light into the ends of the loop and observing the magnified pattern of the fibre ends either photographically or by means of a digital recording of the image pattern. The COBRA Seal System II

(FBOS) employs this technology. Immediately after it is installed, the seal is inserted into a verification assembly that records a reference image of the seal signature pattern. The verifier consists of a verifier head, a still video camera and a liquid crystal display monitor. The verifier head holds the body of a COBRA seal while an image of the seal signature is recorded by the video camera. The image can then be printed and compared with the reference image of the same seal.

TABLE IX. SEALING SYSTEMS

Code	Equipment name	Description and applications
Single use seals		
CAPS	Metallic Seal	Cap seal applied to a wide range of containments for continuity of knowledge of the contents. Verified at IAEA Headquarters after removal.
Improved Adhesive Seal		Commercial sealing tape that cannot be removed without destroying the seal.
In situ verifiable seals		
ACIV	Automatic COBRA Image Verifier	Automatic verifier for COBRA seals.
FBOS	Fibre Optic General Purpose Seal (COBRA)	In situ verifiable fibre optic seal.
ULCS	Ultrasonic Seal (ARC)	Seal used for underwater stack sealing of fuel bundles. It uses a random coil which gives the seal a unique signature. An automated reader compares the signature with a stored value of the seal in situ.
USSB	Ultrasonic Sealing Bolt	General purpose bolt seal primarily used underwater to seal the lids of spent fuel assembly containers.
VCOS	VACOSS-S Electronic Seal (Variable Coding Seal System)	Reusable seal consisting of a fibre optic loop and electronic seal. Light pulses monitor the loop and every opening and closing of the seal is stored in the seal. A palmtop computer reads the seal.
VMOS	VACOSS-S/MOSS System	Unattended system that records the closing (or opening) of VACOSS electronic seals by means of a specially adapted MOSS.

A much more logistically convenient COBRA seal verifier has recently been developed which stores digital images and is able to compare the patterns. This procedure enables the inspector to automatically verify the seal identity and integrity in situ and to conveniently store the pattern in a computer. Figure. 33 illustrates the Automatic COBRA Image Verifier (ACIV) with a COBRA seal.

ULCS, USSB. The Ultrasonic Seal (ULCS) and Ultrasonic Sealing Bolt (USSB) are constructed to contain a unique random pattern of, for example, inclusions of metal pieces in a lighter substrate or a randomly oriented coil of wire. They are applied in a variety of ways, with special designs for different applications. Verification is accomplished by transmitting ultrasonic pulses through the seal with a suitable transducer and observing the unique pattern of reflections. Verification consists of comparing the pattern obtained when installed with that obtained during subsequent in situ checks. These types of seals have proven particularly effective for underwater applications such as for stacks of CANDU fuel bundles (ULCS) or for bolts closing shipment and storage containers of LWR spent fuel assemblies (USSB).

VCOS. Electronic seals will be used with increasing frequency in IAEA applications as remote monitoring becomes more universally applied and as seal manufacture becomes less expensive. The first IAEA electronic seal, originally designed in the late 1970s, was the Variable Coding Seal System (VACOSS-S), shown in Fig. 34. This seal uses electronic encoding methods in conjunction with fibre optic loops. The VACOSS-S Electronic Seal is intended for high reliability, long duration surveillance in applications that require periodic access. The time, date and duration of openings and closings of the loop are recorded internally for later retrieval. The fibre optic loop is interrogated with a light pulse every 250 ms for continuity of the light path. There is no known method of splicing the fibre in the interval between

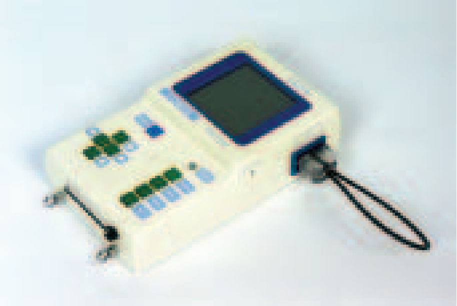


FIG. 33. ACIV: Automatic COBRA Image Verifier with COBRA seal.

FIG. 34. VACOSS-S Electronic Seal with fibre optic loop, interface box and palmtop computer.

interrogations. The internal batteries have a two year operational lifetime. For installations with multiple seals in proximity, the seals may be connected in series. All seals connected in this fashion can be read in sequence without changing the connection. The electronics are potted in an X ray resistant compound of epoxy and ceramic particles to frustrate any possible attempt at reverse engineering. A tamper switch detects any opening of the seal housing. The seal housing is opened only to replace the internal batteries and openings are recorded as tamper events.

5. UNATTENDED MONITORING

Unattended monitoring systems (UMS) run 24 hours a day, 365 days a year, continuously monitoring activities in a variety of nuclear facilities. Each system has redundant sensors and data storage capability and a backup power supply for short term power outages. The systems are designed to maintain continuity of knowledge in a cost effective manner while reducing the costly inspection burden on the IAEA through reduced inspector days in the field. As the number of nuclear facilities continues to increase worldwide, the use of unattended systems to reduce inspection effort in the field becomes more and more critical. Current unattended monitoring systems primarily employ radiation detection sensors to detect the flow of nuclear material past key points in the facility process area. However, the suite of sensors also includes ones capable of measuring temperature, flow, vibration and electromagnetic fields. For complex nuclear facilities where the plant is automated (remotely operated), unattended assay and monitoring techniques are an integral part of the safeguards implementation approach.

Unattended use necessitates that special considerations be included in the instrument design if the system is to be reliable and cost effective in providing credible, independent data. This means that the system must operate without the loss of safeguards relevant data over extended periods, including times when the power supply to a facility is interrupted. The unit should automatically record its status periodically. If data are to be sent over unsecured transmission pathways then the data must be authenticated and encrypted. If data are to be shipped off-site (remote monitoring) then they must be encrypted to meet the requirements of the facility and the State for confidentiality of information and the IAEA requirements for data security. Because of stringent design considerations, unattended and remote monitoring equipment typically has to be flexible, modular and highly reliable.

As part of the preparation for field installation, all systems are carefully tested at the IAEA Safeguards Equipment Support Facility in Vienna using simulated signals. A testing period of at least 90 days, representative of the current unattended period between visits by inspectors, is used. With such testing, early component failure, configuration errors and manufacturing defects can be eliminated while the system and its components are easily accessible during the testing phase in Vienna. Once the system has successfully operated for a full inspection period or approximately 90 days without failure it is ready for field installation.

Unattended safeguards instruments are often deployed in facility areas with limited personnel access, such as areas with a high radiation level. Depending on the facility and the process being safeguarded, the optimum placement of appropriate instruments, even those requiring custom designs, more than justifies the initial high cost when the long term overall economics are considered. Nevertheless, the IAEA is focusing on standardizing all equipment and systems where possible to allow the maximum efficiency in utilizing its limited resources. Custom designs and duplication of capability using different equipment are avoided wherever possible.

The future of UMSs is moving toward fully integrated systems which incorporate direct integration of surveillance systems with local area networks to provide a server-type central collect computer. This is the next logical step in providing the most cost effective approach to the collection of relevant safeguards data. Such a system would use UMS-type sensors to trigger cameras. In this way, image data are significantly reduced to relevant events and the review capability of inspectors is enhanced. Such a system is already in operation at the BN-350 complex in Kazakhstan. A newer integrated version is currently being tested at the Safeguards Equipment Support Facility and scheduled for installation in the Chernobyl Spent Fuel Conditioning Facility in

FIG. 35. The Chernobyl conditioning facility monitoring system being tested in the Safeguards Equipment Support Facility.

the near future. The elements of these systems include an intelligent local operating network (iLON) that interconnects all UMS devices, digital cameras and the collect computer. The iLON controls triggering, time synchronization, local authentication and startup functions. Multi-instrument collect (MIC) software is used to poll all UMS devices to collect the data on a single collect computer using the iLON. After an inspector extracts the data, Radiation Review (RAD Review) is used to examine the data. RAD Review has the capability of viewing the radiation signals received from the system. Its normal suite of options includes peak counting algorithms based on various threshold settings against various expected backgrounds and peak searches. The version at the BN-350 includes a new integration tool in which the digital camera images are also part of the database. For each sensor peak, the inspector can 'click' on the peak of interest and the associated camera image will be displayed. This provides a powerful review tool that integrates two previously separate review functions, allowing for the most cost effective review approach for IAEA inspectors to draw the required safeguards conclusion.

In summary, the primary advantages of unattended verification techniques are:

(a) More effective safeguards through continuous monitoring,
(b) Reduced inspection efforts,
(c) Reduced radiation exposure of inspectors and facility staff,
(d) Reduced level of intrusiveness in the operation of nuclear facilities.

Unattended monitoring systems in use are listed in Table X.

ATPM. Advanced Thermo-hydraulic Power Monitoring is used to monitor the power output of a research reactor and can verify that the output is consistent with the operator declared power level. This system monitors the temperature and water flow in the reactor's primary cooling loop. Because research reactors can modify their core layout and in turn the associated radiation level, this system provides a verification method that is independent of radiation signature. To ensure the necessary fault tolerance, all sensors are installed as duplicate independent sensors (both temperature and flow), whose signals are then independently collected in the main cabinet where they are compared.

This makes it more difficult to falsify the signal and results in a robust system that continues to provide the required inspection data with multiple single point component failures. Aside from the use of tamper enclosures and tamper indicating conduits for the signal cabling, the high sampling rate from the sensors makes it more difficult to send a false signal to the collecting unit.

TABLE X. UNATTENDED AND REMOTE MONITORING SYSTEMS

Code	Equipment name	Description and applications
Unattended Monitoring Systems		
ATPM	Advanced Thermohydraulic Power Monitor	Monitoring system that calculates the power output of research reactors by measuring the flow and temperature differential on the primary coolant loop.
CONS	Input Flow Verification System	Radiation monitoring system that tracks the movement of irradiated fuel at a large scale reprocessing plant (CONSULHA).
ENGM	Entrance Gate Monitor	Radiation monitoring system that monitors non-irradiated fuel assemblies containing Pu that are brought into the reactor facility.
REPM	Reactor Power Monitor	Neutron monitoring system placed outside the reactor biological shield to monitor the power level of the reactor.
UFFM	Unattended Fuel Flow Monitor	Generic radiation monitoring system that monitors the flow of fresh and irradiated fuel in a reactor facility. Placement and details of radiation detectors are facility dependent.
VIFB	CANDU Spent Fuel Bundle Counter	Radiation monitoring system that counts irradiated fuel bundles as they are discharged to the spent fuel storage bay of an on-load refuelled power reactor.
VIFC	CANDU Core Discharge Monitor	Radiation monitoring system that monitors the discharge of spent fuel bundles from an on-load refuelled power reactor core (reactor may be on-power or shut down).

UFFM. The Unattended Fuel Flow Monitor consists of separate neutron or γ ray detector assemblies permanently installed in a reactor facility. These detectors are installed in pairs allowing for the necessary fault tolerance so that no critical safeguards data are lost. The detectors monitor the movement of fresh fuel assemblies to the reactor (for those reactors utilizing MOX — mixed oxide fuel that contains plutonium — such as breeder reactors and LWRs on a MOX cycle), spent fuel assemblies from the reactor to the fuel storage pond,

FIG.. 36. Advanced Thermo-hydraulic Power Monitoring.

and spent fuel assemblies out of the storage pond. Neutron detection in the UFFM is contingent on shielding the neutron detectors from the intense gamma radiation from the spent fuel. The sealed detector systems may be attached to massive transport vehicles or to the storage pond wall near the underwater entrance. Using both neutron and gamma detectors also makes signal substitution by an adversary extremely difficult.

A typical transfer sequence involving several UFFM units could include a fresh fuel assembly being brought to the reactor core and a spent fuel assembly being retrieved and brought to the storage pond. The combination of neutron and γ ray signatures at the successive units characterizes the transferred material as fresh fuel, spent fuel or another material (e.g. neutron irradiated blanket material at a breeder reactor facility). Although individual systems are facility specific, the neutron detectors on the transport vehicles are typically ^{3}He proportional counters or fission chambers and the γ ray detectors are typically NaI scintillators or ionization chambers. Underwater in the storage pond the neutron detector is usually a ^{10}B lined gas filled proportional counter and the γ ray detector is a gas filled ionization chamber. UFFMs are designed to monitor neutron and γ ray counts continuously but store only data that are significantly above background levels. The IAEA is in the process of upgrading all data generators that collect this data with removable flash memory capable of storing at least 100 days of data. This is equivalent to the current inspection period and ensures the necessary fault tolerance in case of computer failure. Surveillance cameras normally complement a UFFM over the fuel transfer route.

ENGM. The Entrance Gate Monitor is included at plutonium fuelled reactor facilities which incorporate the UFFM. This is a permanently installed passive neutron coincidence collar detector (PNCL). Fresh fuel assemblies entering the reactor facility must pass through the ENGM so that their Pu content can be verified. Therefore the ENGM is the system which verifies the amount of fresh fissile fuel in an assembly and serves as the first detector in a sequence of detector systems which follow the movement of fuel assemblies within the reactor facility.

VIFB. The CANDU Spent Fuel Bundle Counter (Fig. 37) is an unattended system that monitors a strategic location in the spent fuel bundle pathway of an on-load refuelled power reactor. Collimated γ ray detectors detect the fuel bundle as it passes. The proper placement of detectors and the use of the appropriate algorithm for the facility enable the device to count the bundles as they pass and record the direction in which they are moving, even when two bundles are moving together, which is normally the case.

High operational reliability, great dynamic detection sensitivity (to include all operational possibilities) and insensitivity to power outages are some of the important features of the bundle counter. Sufficient redundancy was built in to accommodate individual component failures without compromising operation.

VIFC. The CANDU Core Discharge Monitor is a typical unattended monitoring system operating in an inaccessible area. The VIFC detects irradiated fuel upon discharge from the core face of a CANDU reactor.

Both neutron (normal on-power discharge signal) and γ ray intensities are continuously monitored. The inspector, upon reviewing the data, is able to identify in a straightforward, unambiguous manner the abrupt but characteristic change in count rate associated with fuel bundle discharge. The review technique is valid for irradiated fuel discharge both when the reactor is on-power and when it is shut down. Because of the linear increase in background signal, the system can also track the operating power level of the reactor.

The VIFC was designed to be fail-safe. Sufficient redundancy was built in to accommodate individual component failures without compromising

FIG. 37. VIFB: CANDU Spent Fuel Bundle Counter.

operation (failure of the VIFC would be exceedingly difficult to recover from in safeguards terms). The detection modules are designed to last the lifetime of the reactor, since their location inside the containment area limits possibilities for maintenance and repair. Automatic performance and failure monitoring have been incorporated in the VIFC.

6. REMOTE MONITORING SYSTEMS

Remote monitoring in the safeguards context is generally considered to mean that data are transmitted off-site to IAEA Headquarters or to an IAEA field office. Cost effectiveness is a prime justification for adding this feature to surveillance, electronic seals and other unattended systems. If data can be sent to the inspector then the frequency of inspection visits to the facility can be reduced, thus saving both time and expense. In principle, a remote monitoring system with 'state of health' reporting can also function significantly more reliably than an unattended system that is serviced at a set frequency. Some events that would ultimately lead to a failure of the system can be remotely evaluated and reported in time for appropriate action to be taken. Limited IAEA human resources, an ever growing stockpile of nuclear material and economics are likely to accelerate the implementation of remote monitoring in the near future.

Utilizing remote monitoring (RM) as an additional safeguards tool has been under consideration by the IAEA for over two decades. In October 1996, the IAEA Department of Safeguards established its Remote Monitoring Project (RMP). Its chief objectives were the definition and development of a remote monitoring infrastructure and its implementation using available technologies. More specifically, the RMP devised a safeguards policy for remote monitoring, defined approaches and procedures for LWRs, storage sites and on-load reactors, specified basic RM equipment, conducted field tests, undertook cost–benefit analysis of two countries and developed a Departmental plan for the implementation of RM. Upon its completion in December 1998, the plan was approved by the Department, allowing RM to move to the implementation phase with responsibilities divided among the Operations and Support Divisions.

As of June 2002, the IAEA had 54 digital surveillance systems with RM capability installed worldwide. Of those, 33 systems with 71 cameras are operating in the RM mode. In addition to the deployed systems, further work is currently under way to provide additional monitoring features so that RM can be extended to other equipment types.

6.1. REMOTE MONITORING EQUIPMENT

The IAEA's RM equipment is based on systems which can be integrated with a server running the Microsoft Windows NT operating system. At present, only C/S components have reached a sufficient level of maturity to be authorized for inspection use. However, other unattended monitoring systems are currently under development and evaluation to complement and supplement the basic C/S devices, allowing the remote monitoring of more complex facility types.

The development of the DCM14 digital camera module was an important milestone in making RM possible. The DCM14 provided the IAEA with a single device that could digitize the output from a standard video camera, convert the analog video into digital images that could be further compressed, authenticated and encrypted if required. The device also provided the capability to store images and status data on internal removable media and to transmit those images and data to an external data collector.

The IAEA's central data collection and communications controller for field deployment is the Server Digital Image Surveillance (SDIS) system. Aside from allowing the connection of digital cameras to VACOSS seals, the SDIS server also provides the capability to encrypt data and communicate with the IAEA's offices over a variety of communication links, including PSTN, ISDN and satellite. It is also planned that the SDIS server will be connected, via an Ethernet link, with other UMSs to transmit encrypted data. In addition to the SDIS, the IAEA is currently testing the Digital Multi-Camera Optical Surveillance System for remote monitoring where comparatively large numbers of cameras are required.

6.2. FUTURE DEVELOPMENT ACTIVITIES

From the analyses to date, it is clear that RM implementation costs depend on facility type, monitoring system used and the country's communications costs and its nuclear fuel cycle. In addition, Integrated Safeguards may not justify the incorporation of RM at LWRs in countries in which the Additional Protocol is already in force or expected to be in force in the near future. It has therefore been decided that all proposals for the incorporation of RM into inspection activities will be subject to a cost–benefit analysis prior to approval to proceed. To date, Operations divisions have proposed installations in a further 10 countries. Those proposals will be subjected to a rigorous cost–benefit analysis.

The challenge for safeguards now is to further reduce RM implementation costs. Areas have already been identified where it has been suggested that significant cost savings may be possible. The following are examples.

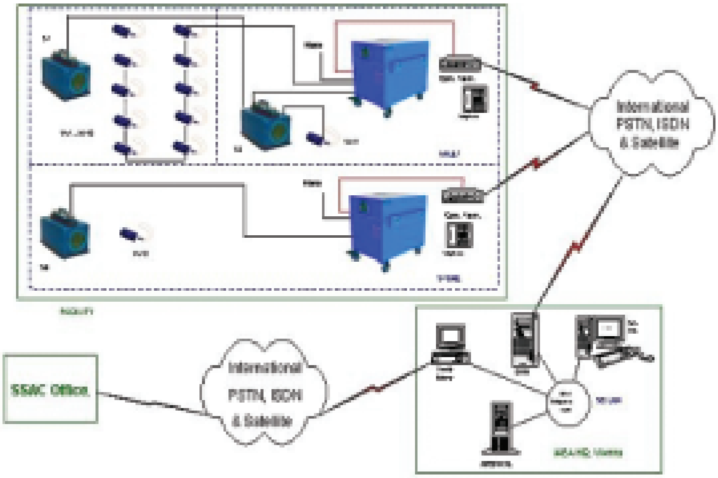


FIG. 38. Remote monitoring schematic.

6.2.1. Data reduction

Currently, all images and data are collected on-site and transmitted to IAEA offices. While the inspectorate has a high degree of confidence that activities of safeguards significance will be fully captured if the picture taking interval is set properly, excessive amounts of data are transmitted due to the large number of images. This results in high communication costs even though a large proportion of those transmitted images contain scenes of no safeguards significance or are redundant.

By employing techniques to detect only images where a change has occurred or where an associated event triggers surveillance, it would be possible to reduce the amount of redundant and non-safeguards relevant data transmitted. Based on previous IAEA studies, the use of scene change detection on fixed time interval recordings (SCD) can reduce the number of redundant scenes and scenes of no safeguards significance by up to 90%. All DCM14 based systems are SCD capable. The IAEA is currently building up its field experience over the wide range of facility types so that it may be in a position to fully accept such techniques with a high degree of confidence.

6.2.2. Alternative communication methods

Currently, the IAEA uses PSTN, ISDN, frame relay and INMARSAT to link remote sites to communication hubs or directly to the IAEA offices. High costs are associated with the use of these conventional dial-up, network and

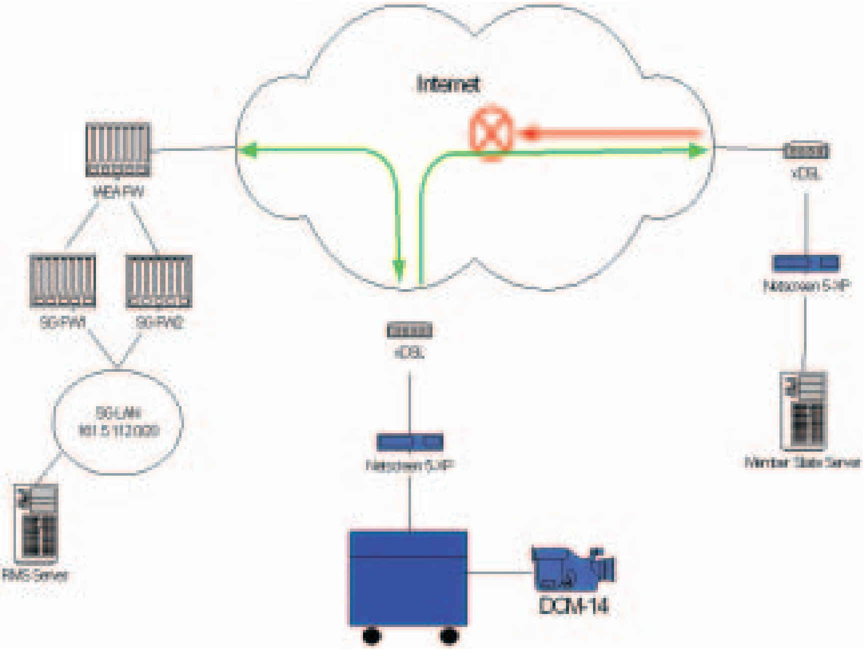


FIG. 39. Remote monitoring over a VPN.

satellite services. Where available, the Internet provides comparatively low cost data communications. By establishing a virtual private network (VPN) using an Internet service provider as the carrier, the IAEA may be able to take advantage of the economies of scale associated with these recent, alternative communication methods. Virtual private networkss can provide possible solutions to security concerns. Some typical commercial estimates predict savings of 20–40% over a leased line and from 60–80% over a dial-up service.

7. DATA SECURITY

Data security is an important feature of unattended and remote monitoring systems. In fact those types of safeguards systems permanently installed at facilities and periodically visited by inspectors transmit data between different system components and between systems and IAEA Headquarters through unsecured transmission paths. Those data need to be cryptographically authenticated to guarantee that they are genuine and may need to be encrypted to prevent disclosure to the host or to ensure confidentiality to the Member States.

Security requirements are defined to meet a security target, and in terms of the types of security services required and the required strength of those services. Table XI provides a list of security services.

In the list, the 'Authentication Security Service' is identified as a separate service although it is often used as a supporting security service for others. For example, confidentiality cannot be guaranteed, even if the data are encrypted, if the receiver's identity is in doubt (i.e. the sender is unsure of who can decrypt the data). Similarly, integrity protection is of little value if the originator's identity is in doubt.

7.1. INFORMATION PROTECTION REQUIREMENTS

To simplify the application of the security architecture and specifically to allow the presentation of a limited set of 'robustness levels' for cryptographic approaches, each information type is assessed in terms of the length of time its security needs to remain uncompromised. This, along with the threat level, will determine the strength (robustness) of the approach and the algorithms selected.

Safeguards information used in unattended and remote monitoring systems can be described by the general information model shown in Fig. 40 and summarized in Table XII. This model is derived from the IAEA Policy Paper on Remote Monitoring[1] and extended to add 'control data'. The model segregates the data on the basis of its intended use as follows:

---

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Remote Monitoring for Safeguarding Nuclear Facilities, Safeguards Policy Series No. 16, IAEA, Vienna (1998).

TABLE XI. SECURITY SERVICES*

Security service	Ensures that	How it is accomplished (‘mechanism’)
Confidentiality (including traffic flow analysis and data separation)	The information is kept private	Information is encrypted. Data are padded to prevent traffic flow analysis. Barriers (e.g. firewalls) prevent improper data flow (e.g. covert channel). Confidentiality requires authentication of receiver(s).
Integrity (including replay/data substitution protection)	The information has not been altered and is not a copy of previous data	‘Signature’ over the data allows detection of alterations. Inclusion of counter/time value prevents replays. Integrity requires authentication of origin.
Access control	Only authentic user with sufficient authority can access the resource	Users prove their identity and authority using trusted means
Non-repudiation	Users cannot later deny their action (‘assertion’)	User includes information (signature) only they could create. Non-repudiation implies authentication of user. May require time stamp.
Authentication	The user is who they say they are	Users prove their identity using trusted authentication means (password, possession of unique object, biometrics).
Availability (including intrusion detection, resistance to attacks)	The systems are operating, unauthorized activities do not compromise operation	Systems are immunized against attack (e.g. firewalls are deployed), mechanisms report attacks to the response agent. Prevention of denial-of-service attacks.
Audit	Accountability is maintained for all significant events	Generate reports (audit messages) when significant events occur. Integrity and guaranteed delivery of all reports is required.
Assurance	All required functions are present in deployed equipment	The design and its implementation have been thoroughly reviewed.

* Derived from the Open Systems Interconnection (OSI) Security Framework, the Information Assurance Technical Framework (IATF) and the Common Criteria (CC).

TABLE XII. SUMMARY OF UNATTENDED AND REMOTE MONITORING DATA TYPES

Data type	Sample data	Data use	Frequency of use
Verification data	Camera image, seal status, operator declaration	Used for safeguard review. Only 'verification data' may be used to draw conclusions about safeguards implementation at a facility.	Period between safeguard reviews depends upon arrangements with facility but will be in the range of one to six months.
Technical data, including summary and state of health data	Number of triggered recordings, battery charge level, tamper indication, equipment temperature, failure indication, audit log data	Used for technical review for: (1) Planning of inspection activities (2) Equipment maintenance and repair or other follow-up activities.	For remote monitoring systems technical reviews are daily but may be delayed by up to three working days. For other systems technical reviews are during on-site visit or soon thereafter.
Control data	Set time of day, set sampling interval, run diagnostic, key management data	Used for control by: (1) Safeguards application programs, (2) IAEA inspectors and technical staff	Real time on-line operations (as implemented).

(a) Verification data are used during safeguards reviews carried out by approved IAEA inspectors,

(b) Technical data are used during technical reviews carried out by approved IAEA technical staff,

(c) Control data are used for the 'real time' control of the equipment either by automated safeguards application programs or manually during inspection or maintenance activities.

Depending on the surveillance design, some technical data may also be included in 'verification data' if deemed important for the safeguards review (shown by dotted lines in Fig. 40). Although some general conclusions may be

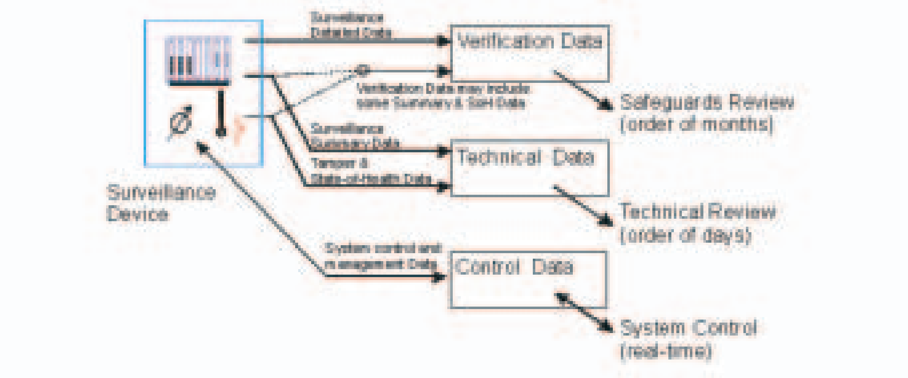


FIG. 40. Unattended and remote monitoring information model.

drawn regarding the data types in the model, there will be exceptions, depending upon the specific design of the unattended monitoring.

7.2. IAEA REQUIREMENTS

This section will address IAEA requirements for securing data. Member State requirements will be addressed in Section 7.3..

7.2.1. Verification data

Unattended and remote monitoring systems data must be analysed using trustworthy data to permit valid conclusions to be drawn. That is, the information used for analysis must be known to have originated from the intended source, must be known not to have been changed in transit, and must be known not to be a repeat of previous data.

The IAEA Policy Paper on Remote Monitoring states the following (see footnote 2):

> “Measures shall be taken to ensure the authenticity of the transmitted and stored data.”

In the above statement the term ‘authenticity’ refers to the combination of integrity (including replay/data substitution) and authentication (of origin) protection, as defined above.

The IAEA requirements for confidentiality are defined as follows:

> "As a general rule, the detailed safeguards information from the Agency equipment should not be made available to the States. However, arrangements could be made for sharing of certain data as part of the cooperation arrangements with the State authorities."

Although integrity and authentication are of primary importance, some safeguards data may require confidentiality protection since knowledge of actually measured values may allow States to exploit instrument characteristics or inaccuracies. For example, if the actual measured value and the instrument accuracy are known, declarations could be manipulated to ensure that each declaration is within the bounds of measurement error while allowing a protracted diversion of small amounts of material.

Non-repudiation (of origin) protection is required for operator declaration data. Depending upon the security mechanism,[2] basic non-repudiation (of origin) may be inherent in the method used for integrity and authentication. Typically, operator declarations will require the time of the declaration to be included if there may be a significant delay in the delivery of the declaration to the IAEA. If a declaration is delivered to the IAEA quickly, it can securely archive the information upon receipt and be in a position to confirm that it has not been replaced with a later declaration. On the other hand, if there may be a delay in delivery, a time stamp would be required.

Non-repudiation, integrity and authentication protection, and confidentiality protection when needed, must be strong enough to withstand external attacks. As indicated above, not all of the information may require confidentiality protection, and even when required this protection may only be needed for a limited time period. For example, measurement data may only be sensitive until the corresponding Member State declaration has been made.[3]

---

[2] For example, if public key based signatures are used basic non-repudiation of origin is provided. Stronger non-repudiation protection requires additional mechanisms to bind the time of signing to the signature. For example, a copy (or digest, complete with the user's signature) of the message could be stored in a trusted storage facility so that evidence is available that the signature was applied at a particular point in time. Alternatively, a copy (or digest and signature) might be sent to a trusted time stamping service that would add a time value and sign the overall combination. Trusted time stamping services and trusted storage facilities may also be required to support other security services such as trusted auditing and tracking.

[3] This may not be true in all cases. Long term analysis of instrument data inaccuracy may allow the prediction of future inaccuracies. In such cases instrument data may need to be protected until the instrument is recalibrated.

Thus, although non-repudiation, integrity and authentication protection will be required throughout the life of the verification data (i.e. many years), confidentiality protection may[4] only be required until the safeguards review has been completed (e.g. a few months).

7.2.2. Technical data

The IAEA Safeguards Glossary[5] points out that:

> "Receiving state of health data with a sufficient frequency makes it possible to detect failures of equipment or tampering early enough for remedial actions to be implemented to satisfy the timeliness requirements."

The IAEA Policy Paper on Remote Monitoring (see footnote 2) states that:

> "Data remotely transmitted to Headquarters or Regional Offices are normally subject to a daily technical review. If this is not possible, there should be no more than three consecutive working days without review. The technical review includes monitoring of state-of-health messages and tamper reports."

The objective is to transfer these data as quickly as possible to permit remedial action to be initiated. In practice however, and especially for unattended monitoring systems not connected to a data network, the receipt of these data may be delayed until an inspector arrives at the site.[6]

All technical data require integrity and authentication protection to ensure that failures, logs and indications of tampering are reliably reported to IAEA staff. Additionally, for data which may indicate increased equipment vulnerability, confidentiality protection will be required until remedial action can be taken. For example, state-of-health data indicating a failure of internal backup battery power may indicate an increased vulnerability to the removal

---

[4] More sophisticated attacks might use historical data to predict future instrument errors. In such cases confidentiality protection would be required until the equipment is recalibrated.

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safeguards Glossary, 2001 Edition, IAEA/NVS/3, IAEA, Vienna (2002).

[6] A networking failure at a site may delay state-of-health data delivery even for networked systems.

of primary power. Such an indication might allow a threat agent to optimize their attack on the equipment.

The integrity and authentication protection, and confidentiality protection when needed, must be strong enough to withstand external attacks. It would appear that such protection may only be needed for a limited period of time. For example, state of health data may only be sensitive until the equipment can be maintained. Thus protection may only be required until the technical review is complete and remedial action has been taken.

It may be appropriate to provide integrity and authentication protection to some audit and other information for longer periods if its relevance cannot be determined during the initial technical review. Historical trends may have to be analysed to arrive at conclusions. In such situations this information may also be included in the verification data.

7.2.3. Control data

At present, equipment control data are not commonly used in unattended and remote monitoring systems. However, control data will be used increasingly to permit sensors to be adjusted and controlled from the collect computer, and eventually to permit remote monitoring systems to be controlled from IAEA premises. Control data are transmitted in ‘real time’ and might include:

(a) The distribution of common time values to sensors by the collect computer,
(b) The control of sensor operation (e.g. camera focus, pan/tilt, sampling rate),
(c) The activation of test and calibration routines in sensors.

In the future, and provided that adequate security measures can be put into place, the overall remote monitoring system might be controlled from IAEA offices. In such cases it will be necessary to ensure that remote log-in and access controls are adequate to ensure the secure control of the equipment. Typical control information might include:

(1) Secure log-in to the collect computer,
(2) The initiation of file and data transfers,
(3) Operational control of the remote monitoring system,
(4) The activation of test routines in the collect computer,
(5) The secure entry of commands into the collect computer which may in turn issue secure controls to attached sensors,
(6) The updating of software.

Integrity and authentication protection are required for all such data to prevent their modification. Confidentiality is required for some control data since observation may reveal sensitive information such as the criteria used to adjust surveillance triggers.[7] Access control and availability protection must be provided to prevent threat sources from masquerading as authentic sources of control data and to prevent denial of service attacks at the communications ports. Control commands can also be susceptible to traffic analysis, whereby an observer gathers knowledge from an analysis of traffic patterns. For example, even if a command is encrypted, if the command results in a higher rate of data transmission an observer can likely draw valid conclusions about the content of the command.

All required protection measures must be strong enough to withstand external attacks. These measures are required throughout the lifetime of the data.

7.3. MEMBER STATE REQUIREMENTS

Member State concerns mainly relate to ensuring that their information is kept confidential and ensuring that the safeguards programme reliably reflects their conformance to the agreements.

The Model Safeguards Protocol[8] states in part that:

> “Article 14:
>
> b. Communication and transmission of information … shall take due account of the need to protect proprietary or commercially sensitive information or design information which the Member State regards as being of particular sensitivity.
>
> Article 15:
>
> a The Agency shall maintain a stringent regime to ensure effective protection against disclosure of commercial, technological and

---

[7] Confidentiality protection of time of day update control data may not be needed.

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards, INFCIRC/540, IAEA, Vienna (1997).

> industrial secrets and other confidential information coming to its knowledge, including such information coming to the Agency's knowledge in the implementation of this Protocol."

The IAEA Policy Paper on Remote Monitoring (see footnote 2) states that:

> "Encryption should be applied during data transmission, as agreed with the State.
>
> Transmitted data shall be treated and stored as 'Safeguards Confidential' information.
>
> States have the right to know the kind of information being transmitted, and to the protection of the data through appropriate encryption. As a general rule, the detailed safeguards information from the Agency equipment should not be made available to the States. However, arrangements could be made for sharing of certain data as part of the cooperation arrangements with the State authorities. The arrangements for sharing such data shall be approved by the Deputy Director General — Safeguards on a case by case basis."

It is noted that these Member State requirements are specifically directed towards protecting the confidentiality of 'commercial, technological and industrial secrets'. This Member State requirement for confidentiality will not normally require additional security mechanisms while the information is contained within the physically secure facility provided by the Member State. This Member State requirement will normally only apply to information while it is within communications networks provided by the IAEA, on transportable media, or within IAEA offices or inspection equipment. Exceptions to this may occur if sensors and collect computers are not within a single contiguous facility (and thus require a data link through unprotected areas) or if the facility communications links are otherwise exposed (e.g. due to the use of wireless links or the use of facility networks shared with other users).[9]

---

[9] Such deployments are not expected. The use of wireless networks and shared networks is not recommended but may be required due to the constraints on specific installations.

For UMS and RMS, and for the purposes of this security architecture, Member State confidentiality requirements impact two areas:

(1) Ensuring that adequate protection is provided for data links between sensors and collect computers if not otherwise protected by physical boundaries provided by Member States,
(2) Ensuring adequate protection of the data stored on transportable media.

In addition, if the security of laptop computers used by inspection and technical staff is not addressed elsewhere, it will be important to ensure that any Member State information stored or viewed on these devices is adequately protected.

The confidentiality protection must be strong enough to withstand external attacks. Since the owner of the information being protected is in the best position to judge the value of their data, provision will need to be made to satisfy the protection strength specified by Member States. In the absence of specification by a Member State, the IAEA's security architecture specifies a minimum strength level suitable for general commercial practice and equivalent to the 'Safeguards Confidential' specified by the IAEA.

8. ENVIRONMENTAL SAMPLING

Environmental sampling was introduced in 1996 as one of the new IAEA safeguards measures which contribute to the confirmation of the absence of undeclared nuclear material or nuclear activities. Collection of environmental samples at or near a nuclear site combined with ultrasensitive analytical techniques such as mass spectrometry, particle analysis and low level radiometric techniques, can reveal signatures of past and current activities in locations where nuclear material is handled. Initial implementation of environmental sampling for safeguards is focused on the collection of swipe samples inside enrichment plants and installations with hot cells. Implementation is being extended to other types of nuclear facilities and samples collected in connection with complementary access inspection activities under the Additional Protocol.

Samples are analysed in either bulk or particle mode, depending on the sampling objectives and the activity levels of the swipes. Bulk analysis involves the analysis of an entire sample, usually by γ ray spectrometry or isotope dilution thermal ionization mass spectrometry; the analytical measurements represent average results for the material contained. Particle analysis relies on the detection and analysis of individual particles in the micrometre size range and provides as results the U and Pu content as well as isotope ratios of U and/or Pu in these particles.

8.1. IAEA CLEAN LABORATORY FOR SAFEGUARDS

The IAEA Clean Laboratory for Safeguards (Fig. 41) was inaugurated in December 1995 with the goal of providing a Class 100 clean-room capability for the provision and certification of sampling kits and for the receipt, screening and distribution of environmental samples from safeguards inspections. This facility significantly reduces the risk of cross-contamination that might lead to incorrect safeguards conclusions. The Clean Laboratory consists of over 200 m^2 of laboratory space, with approximately 50 m^2 at the ISO Class 5 cleanliness level (Fig. 42). The laboratory is equipped with a suite of analytical techniques, including α, β, γ and X ray fluorescence spectrometry, scanning electron microscopy with electron probe analysis and high sensitivity thermal ionization mass spectrometry.

Environmental swipe samples received at the Clean Laboratory are given a code number to maintain confidentiality about their origin. The samples are then measured by low background γ ray spectrometry to detect the presence of actinide elements (primarily U and Pu) and fission or activation products (such

FIG. 41. The IAEA Clean Laboratory for Safeguards.

as ^{60}Co, ^{137}Cs and ^{106}Ru); the samples are then measured by X ray fluorescence spectrometry to detect the presence of U, Pu or other important elements. Alpha/beta counting is then applied to radioactive samples to detect actinides or β emitting isotopes such as ^{3}H, ^{90}Sr or $^{99}Tc^{m}$.

Following the screening measurements, subsamples are distributed to laboratories of the NWAL for more detailed analysis. Selected samples are chosen for measurement in the Clean Laboratory by isotope dilution thermal ionization mass spectrometry, using a highly sensitive instrument equipped

FIG. 42. Analyst working in the clean module of the IAEA Clean Laboratory.

with pulse counting detection. The ultimate sensitivity of this method is in the 10^{-15} g range for U and Pu.

One of the main activities of the Clean Laboratory is the preparation of clean sampling kits for collecting environmental samples. A kit for the collection of swipe samples is shown in Fig. 43. This consists of all the supplies needed by an IAEA inspector in the field: clean swipe cloths, plastic minigrip bags, clean-room gloves, a sample data form, a pen and labels. A roll of aluminium foil is provided to establish a clean working surface. A different type of swipe sampling kit is required for sampling inside hot cells, where the subsamples must be taken with remote manipulators and shipped back to the IAEA in a special lead lined container because of their higher radiation level.

8.2. SCREENING OF SAMPLES

8.2.1. Low level γ ray spectrometry

Immediately after receipt, environmental samples are measured with a low background γ ray spectrometer system. The spectrometer is based on a 90% efficient coaxial Ge detector enclosed in a high purity lead shield of 10 cm thickness. The samples, in special beakers, are placed in a 15 position sample changer and counted for 1 h each to provide a γ ray spectrum in the energy range from 5 keV to 3 MeV. The total γ activity, corrected for background, is obtained by this method and if sufficient activity is detected, an evaluation of the spectral peaks can be performed to estimate the activity in the sample of

FIG. 43. Cotton swipe kit for environmental sampling.

individual γ emitting isotopes such as ^{60}Co, ^{95}Zr, ^{106}Ru, ^{134}Cs, ^{137}Cs and ^{241}Am. Depending on the number of counts collected, the precision and accuracy of these measurements are in the range 2–5%rel. The absolute activity of individual radioisotopes is not as important as the relative activity compared with a selected isotope such as ^{137}Cs.

8.2.2. X ray fluorescence spectrometry

X ray fluorescence spectrometry is used to detect microgram amounts of U, Pu or other elements of interest on the surface of swipe samples. The sample is held by a robot arm and irradiated by X rays from an X ray tube, resulting in the emission of fluorescent X rays from elements present on the swipe. The fluorescent X rays are detected using a 100 mm^2 Si(Li) detector placed near the sample. Counting is performed for 4–5 hours and the spectra are then evaluated to determine the amount of the element present as well as its spatial distribution. The screening method is completely non-invasive because the subsample can be measured inside its plastic bagging.

8.2.3. Alpha/beta counting

A gridded ionization chamber counting system is used to screen radioactive swipe samples for the presence of α or β emitting isotopes. The swipes are subsampled with an adhesive carbon disc, which is placed in the counting chamber and measured for one hour.

This system has high collection efficiency and has a sensitivity in the millibecquerel range. Alpha emitting nuclides such as ^{210}Po and β emitters such as ^{3}H, ^{90}Sr and ^{99}Tc^{m} can be measured much more sensitively in this way than by γ or X ray methods.

8.3. ISOTOPIC AND ELEMENTAL ANALYSIS

8.3.1. Pulse counting thermal ionization mass spectrometry

Screening measurements are used to decide which samples should be sent for more detailed analysis. Thermal ionization mass spectrometry is used to measure U and Pu concentrations and isotopic compositions in environmental samples. The basic technique was described in Section 3. However, for measurements of environmental samples a much higher sensitivity is needed, extending into the l0^{-9} and 10^{-12} g ranges. This is achieved by the use of special sample treatment procedures, drop deposition of the sample elements onto the mass spectrometer filament and use of a pulse counting detection system with high detection efficiency. The mass spectrometer is shown in Fig. 44.

Isotopic spikes (^{233}U, ^{242}Pu or ^{244}Pu) are added to the samples during chemical processing to allow U or Pu concentrations to be determined using the isotopic dilution method. Isotope ratios are measured for all isotopes of U or Pu relative to the spike isotope and the isotopic composition of the sample is estimated by subtraction of the known isotopic composition of the spike. The accuracy and precision of this technique are about 1–10% for a U or Pu concentration in the 10^{-9} g range and for the ratios of the major isotopes in the sample.

8.3.2. Scanning electron microscopy with electron probe analysis

The Clean Laboratory is equipped with a scanning electron microscope with wavelength and energy dispersive X ray fluorescence detectors (Fig. 45). Particles of interest are removed from the sample using adhesive carbon discs, which are introduced into the electron microscope. Under high magnification (500—5000×) the particles are examined and the backscattered electron signal is used to search for particles containing heavy elements. These particles can then be measured by energy dispersive X ray fluorescence spectrometry to give a semiquantitative elemental analysis. Particles containing U or Pu can be identified in this way; their size and morphology, as well as other elements present, will give information about the process that created them. This type of

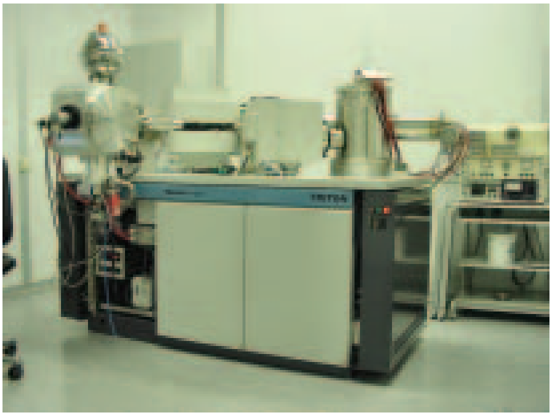


FIG. 44. Mass spectrometer for environmental isotopic analysis.

FIG. 45. Scanning electron microscope for particle analysis.

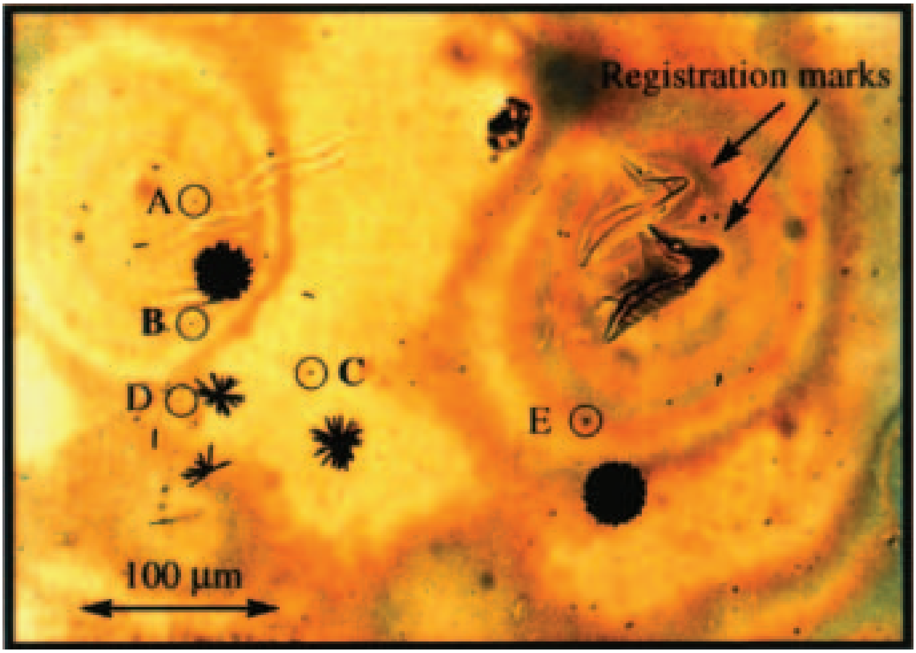
analysis forms a part of the classical ‘particle analysis’ approach which is applied in certain NWAL laboratories in conjunction with thermal ionization mass spectrometry.

8.3.3. Fission track method

Traditional particle analysis first involves a step in which particles of interest containing fissile isotopes such as ^{235}U or ^{239}Pu are selected by the fission track method. The particles are then mounted onto the filament of a thermal ionization mass spectrometer for measurement of the isotopic composition of the U and Pu present.

The fission track method involves removal of particles from the environmental sample by ashing (for vegetation or swipe samples) or physical removal by ultrasoneration in an inert solvent. The particles are then spread onto a plastic track etch film (e.g. Lexan) in a layer of collodion (nitrocellulose). The film is then irradiated in a reactor with thermal neutrons at a total dose of 10^{14} neutrons. Particles containing fissile isotopes leave damage tracks in the film, which can be etched to make them visible under a light microscope (Fig. 46). An experienced analyst can compare the size and appearance of the particles with the number of fission tracks to decide which particles should be measured further. The analyst can then pick up each particle of interest and mount it directly onto a filament for thermal ionization mass spectrometry.

For thermal ionization mass spectrometry, the particle is held in a rhenium metal filament and heated in the ion source of the mass spectrometer



Particle	Size (µm)	Tracks	%U-235	Compound
A	1.2	100	3.0	UO_2
B	1.0	19	0.5	UO_2
C	1.5	40	0.5	UO_2
D	0.7	8	0.5	UO_2
E	1.5	600	91.8% ^{239}Pu	PuO_2

FIG. 46. Lexan film showing fission tracks.

at 1500–1800°C to produce ions of U or Pu, which are counted by a pulse counting detection system. The mass spectrometer steps between the isotopes of U or Pu to accumulate a mass spectrum. The abundance of the various isotopes can be estimated from the collected ion counts with a precision and accuracy of better than 1%rel. for isotopes of 1–90% abundance in particles with a diameter of 1–5 µm. Particles with diameters down to 0.1 µm can be measured, but with less precision and accuracy.

8.3.4. Secondary ion mass spectrometry

Another technique used in SAL and certain network laboratories for measuring the isotopic composition of micrometre size environmental particles is secondary ion mass spectrometry (Fig. 47). The particles are deposited on a conducting substrate and placed in the vacuum system of the instrument where they are bombarded with energetic ions of oxygen. The ion bombardment results in sputtering of the sample and the ejection of secondary ions which are representative of the particle under examination. The secondary ions are accelerated and mass analysed by the spectrometer and counted with either an imaging or pulse counting ion detector. In the ion microscope mode of operation, an image is generated using secondary ions of a given mass (e.g. $^{235}U^+$). Another image can then be taken using a different secondary ion signal (such as $^{238}U^+$) and the two images merged to obtain the $^{235}U/^{238}U$ ratio for each particle in the field of view (typically 150 µm in diameter). By scanning 100–200 fields in one session, it is possible to interrogate several thousand particles by this method, thus giving a distribution of the ^{235}U enrichments found in the particles from a sample.

Once an interesting particle has been identified in the ion microscope mode, it can be measured to completion by focusing the primary ion beam on it and stepping between the isotopes of interest. This will yield the complete isotopic composition of the particle, including the minor isotopes such as ^{234}U and ^{236}U. Depending on the size of the particle, the precision and accuracy of this approach can be 1%rel. for isotopes at the 1–90% abundance level and up to 10%rel. for minor isotopes.

FIG. 47. Secondary ion mass spectrometry (SIMS).