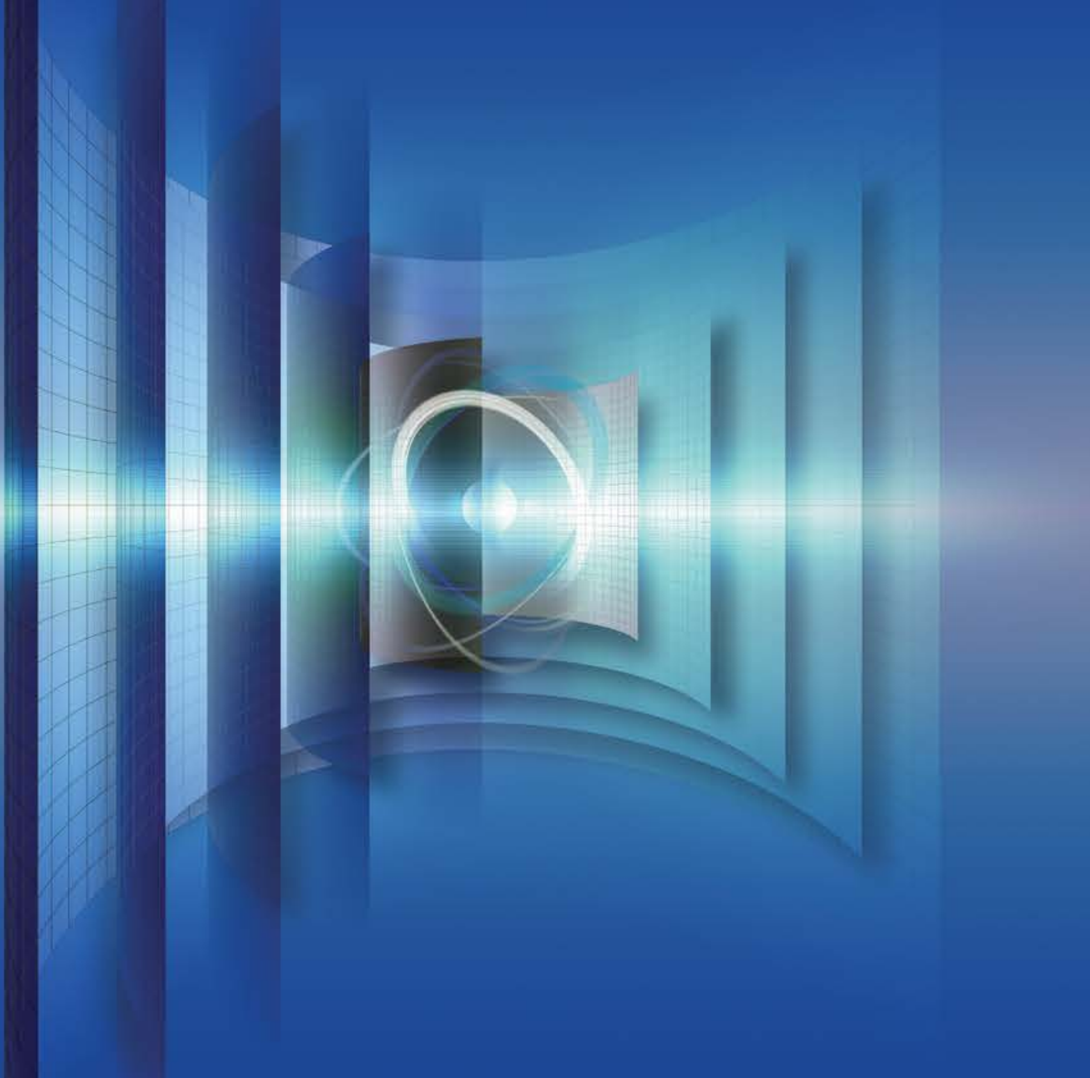
IAEA Nuclear Security Series No. 2-G (Rev.1)

Implementing Guide

Nuclear Forensics in Support of Investigations



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IAEA NUCLEAR SECURITY SERIES

Nuclear security issues relating to the prevention and detection of, and response to, criminal or intentional unauthorized acts involving, or directed at, nuclear material, other radioactive material, associated facilities or associated activities are addressed in the **IAEA Nuclear Security Series**. These publications are consistent with, and complement, international nuclear security instruments, such as the Convention on the Physical Protection of Nuclear Material and its Amendment, the International Convention for the Suppression of Acts of Nuclear Terrorism, United Nations Security Council resolutions 1373 and 1540, and the Code of Conduct on the Safety and Security of Radioactive Sources.

CATEGORIES IN THE IAEA NUCLEAR SECURITY SERIES

Publications in the IAEA Nuclear Security Series are issued in the following categories:

- **Nuclear Security Fundamentals** specify the objective of a State's nuclear security regime and the essential elements of such a regime. They provide the basis for the Nuclear Security Recommendations.
- **Nuclear Security Recommendations** set out measures that States should take to achieve and maintain an effective national nuclear security regime consistent with the Nuclear Security Fundamentals.
- **Implementing Guides** provide guidance on the means by which States could implement the measures set out in the Nuclear Security Recommendations. As such, they focus on how to meet the recommendations relating to broad areas of nuclear security.
- **Technical Guidance** provides guidance on specific technical subjects to supplement the guidance set out in the Implementing Guides. They focus on details of how to implement the necessary measures.

DRAFTING AND REVIEW

The preparation and review of Nuclear Security Series publications involves the IAEA Secretariat, experts from Member States (who assist the Secretariat in drafting the publications) and the Nuclear Security Guidance Committee (NSGC), which reviews and approves draft publications. Where appropriate, open-ended technical meetings are also held during drafting to provide an opportunity for specialists from Member States and relevant international organizations to review and discuss the draft text. In addition, to ensure a high level of international review and consensus, the Secretariat submits the draft texts to all Member States for a period of 120 days for formal review.

For each publication, the Secretariat prepares the following, which the NSGC approves at successive stages in the preparation and review process:

- An outline and work plan describing the intended new or revised publication, its intended purpose, scope and content;
- A draft publication for submission to Member States for comment during the 120 day consultation period;
- A final draft publication taking account of Member States' comments.

The process for drafting and reviewing publications in the IAEA Nuclear Security Series takes account of confidentiality considerations and recognizes that nuclear security is inseparably linked with general and specific national security concerns.

An underlying consideration is that related IAEA safety standards and safeguards activities should be taken into account in the technical content of the publications. In particular, Nuclear Security Series publications addressing areas in which there are interfaces with safety — known as interface documents — are reviewed at each of the stages set out above by relevant Safety Standards Committees as well as by the NSGC.

NUCLEAR FORENSICS
IN SUPPORT OF INVESTIGATIONS

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

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NUCLEAR FORENSICS IN SUPPORT OF INVESTIGATIONS

IMPLEMENTING GUIDE

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FOREWORD

by Yukiya Amano
Director General

The IAEA's principal objective under its Statute is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." Our work involves both preventing the spread of nuclear weapons and ensuring that nuclear technology is made available for peaceful purposes in areas such as health and agriculture. It is essential that all nuclear and other radioactive materials, and the facilities at which they are held, are managed in a safe manner and properly protected against criminal or intentional unauthorized acts.

Nuclear security is the responsibility of each individual State, but international cooperation is vital to support States in establishing and maintaining effective nuclear security regimes. The central role of the IAEA in facilitating such cooperation and providing assistance to States is well recognized. The IAEA's role reflects its broad membership, its mandate, its unique expertise and its long experience of providing technical assistance and specialist, practical guidance to States.

Since 2006, the IAEA has issued Nuclear Security Series publications to help States to establish effective national nuclear security regimes. These publications complement international legal instruments on nuclear security, such as the Convention on the Physical Protection of Nuclear Material and its Amendment, the International Convention for the Suppression of Acts of Nuclear Terrorism, United Nations Security Council resolutions 1373 and 1540, and the Code of Conduct on the Safety and Security of Radioactive Sources.

Guidance is developed with the active involvement of experts from IAEA Member States, which ensures that it reflects a consensus on good practices in nuclear security. The IAEA Nuclear Security Guidance Committee, established in March 2012 and made up of Member States' representatives, reviews and approves draft publications in the Nuclear Security Series as they are developed.

The IAEA will continue to work with its Member States to ensure that the benefits of peaceful nuclear technology are made available to improve the health, well-being and prosperity of people worldwide.

EDITORIAL NOTE

Guidance issued in the IAEA Nuclear Security Series is not binding on States, but States may use the guidance to assist them in meeting their obligations under international legal instruments and in discharging their responsibility for nuclear security within the State. Guidance expressed as 'should' statements is intended to present international good practices and to indicate an international consensus that it is necessary for States to take the measures recommended or equivalent alternative measures.

Security related terms are to be understood as defined in the publication in which they appear, or in the higher level guidance that the publication supports. Otherwise, words are used with their commonly understood meanings.

An appendix is considered to form an integral part of the publication. Material in an appendix has the same status as the body text. Annexes are used to provide practical examples or additional information or explanation. Annexes are not integral parts of the main text.

Although great care has been taken to maintain the accuracy of information contained in this publication, neither the IAEA nor its Member States assume any responsibility for consequences which may arise from its use.

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CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. Forensic science, referred to as forensics, is the examination of physical, biological, behavioural and documentary evidence in the context of international or national law. The goal of forensics is to discover linkages among people, places, things and events. Nuclear forensic science is a subdiscipline of forensic science and is referred to as nuclear forensics. Nuclear forensics is the examination of nuclear or other radioactive material, or of evidence that is contaminated with radionuclides, in the context of legal proceedings under international or national law related to nuclear security. The analysis of nuclear or other radioactive material seeks to identify what the materials are, how, when and where the materials were made, and what their intended uses were. The conduct of a nuclear forensic examination must be done both securely and safely to ensure the protection of the public, the environment and the evidence [1].

1.2. In the mid-1990s, there was an increase in the reporting of nuclear and other radioactive material out of regulatory control, the scope of which is defined in international basic safety standards [1], which was considered to indicate an increase in illicit trafficking of such material. This increase in illicit trafficking was recognized as a significant security threat by the international community. To investigate such trafficking incidents involving nuclear and other radioactive material, national authorities required information on the material, how, when and where it had been produced, and its subsequent history. These enquiries led to the inception of nuclear forensics as a key element of a nuclear security infrastructure [2].

1.3. Given the widespread and important use of nuclear and other radioactive material, all States should be aware of the role of nuclear forensics in supporting nuclear security. Nuclear forensics, using capabilities maintained by the State, can assist in investigations of nuclear security events as well as help to identify and remedy vulnerabilities in a State's nuclear security infrastructure. A nuclear forensic capability as a preventive measure is effective because it supports both the identification of deficiencies in material security and the prosecution of criminal offences related to this material.

1.4. In recognition of the benefits of a nuclear forensic capability to the implementation of national nuclear security infrastructures, the IAEA first published technical guidance on this area in IAEA Nuclear Security Series No. 2, Nuclear Forensics Support[1], in 2006, based on a generalized approach to the conduct of a nuclear forensic examination developed by the Nuclear Forensics International Technical Working Group (ITWG) [3]. Since its publication, there have been further advances in nuclear forensics. Nuclear forensic examinations have been successfully applied to a number of reported cases involving the illicit trafficking of high enriched uranium and plutonium, as well as events involving nuclear and other radioactive material out of regulatory control. Techniques similar to those used in nuclear forensics have also been used to support nuclear counterterrorism efforts and compliance with various international legal instruments, such as the Convention on the Physical Protection of Nuclear Material [4]. In light of these developments, the Technical Guidance publication Nuclear Forensics Support has been updated to form the basis for this Implementing Guide.

OBJECTIVE

1.5. The objective of this publication is to provide national policy makers, competent authorities, law enforcement and technical personnel with guidance on the role of nuclear forensics in the context of investigating a spectrum of possible nuclear security events involving nuclear and other radioactive material out of regulatory control. It is intended to describe the role of nuclear forensics in support of investigations of a nuclear security event and provide a context for nuclear forensics within a national nuclear security infrastructure. In addition, this publication promotes international cooperation by encouraging States to seek or provide assistance, where appropriate, with regard to developing capabilities or during an investigation of a nuclear security event.

SCOPE

1.6. This publication provides: descriptions of nuclear forensic examinations; the role of nuclear forensics in a national nuclear security infrastructure, including the investigation of a nuclear security event; and mechanisms for

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Forensics Support, IAEA Nuclear Security Series No. 2, IAEA, Vienna (2006). The 2006 Technical Guidance publication is superseded by this Implementing Guide.

international cooperation and assistance in nuclear forensics. The essential elements of nuclear forensic capacity building, including awareness, education, expertise development and training, are also described. Furthermore, this publication emphasizes that a nuclear forensic capability encompasses more than just instrumentation or analytical measurements. Nuclear forensics involves a comprehensive plan undertaken by States to determine the origin and history of nuclear or other radioactive material in support of law enforcement or nuclear security investigations. Such investigations may include, but are not limited to, illicit trafficking incidents or other encounters with nuclear and other radioactive material out of regulatory control.

1.7. This publication does not provide detailed guidance on the design, equipping or staffing of a laboratory where nuclear forensic examinations may be conducted; nor does the publication provide detailed guidance on radiological crime scene management, the conduct or management of an investigation of a nuclear security event, or traditional forensic examinations, although each of these subjects contributes to the success of a nuclear forensic examination. Traditional forensics includes the examination of physical, biological and documentary evidence conducted in traditional forensic disciplines by investigating authorities. Examples of these disciplines include:

— Fingerprints;
— Genetic markers, such as nuclear DNA and mitochondrial DNA;
— Shoe and tyre impressions;
— Tool marks;
— Explosives, paints and other chemicals;
— Metallurgy;
— Trace evidence, such as fibres, hairs and pollens.

1.8. This publication supports the Nuclear Security Recommendations on Nuclear and Other Radioactive Material out of Regulatory Control [5], issued in 2011, and is complemented by other IAEA Nuclear Security Series publications:

— Combating Illicit Trafficking in Nuclear and other Radioactive Material [6];
— Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5) [7];
— Identification of Radioactive Sources and Devices [8];
— Radiological Crime Scene Management [9].

STRUCTURE

1.9. Following this introduction, Section 2 illustrates the nuclear forensics model action plan and highlights issues for all States to consider in the development of a nuclear forensic capability. Section 3 explains the importance of developing a forensic examination plan and a nuclear forensic analytical plan. Section 4 presents different approaches for performing forensic examinations on evidence contaminated with radionuclides. Section 5 discusses the requirements of a designated nuclear forensic laboratory and the different types of nuclear forensic analysis. Section 6 provides an overview of the methods and processes involved in nuclear forensic interpretation, and Section 7 covers the role of confidence in analytical results and communication of the findings. Section 8 describes international cooperation for nuclear forensics and considerations when requesting nuclear forensic assistance. Section 9 discusses national capacity building activities that should be undertaken in order to develop and maintain nuclear forensic capabilities. Three annexes provide, respectively, more detailed information on techniques for characterization, on other forensic science disciplines and on examples of capacity building activities available internationally. The annexes are followed by the Glossary, in which the definitions have been harmonized with other IAEA and United Nations publications.

2. THE ROLE OF NUCLEAR FORENSICS IN A NATIONAL NUCLEAR SECURITY INFRASTRUCTURE

2.1. Nuclear and other radioactive material is prevalent throughout the nuclear fuel cycle, and is also widely used in other industries and in research, medical and biological studies and other technical and scientific applications. It is a State’s responsibility to implement a nuclear security infrastructure to protect these materials, including measures designed to prevent, detect and respond to nuclear security events. When nuclear and other radioactive material is detected out of regulatory control, States should be prepared to respond appropriately, including applying nuclear forensics in support of investigations. Some examples of nuclear and other radioactive material are shown in Table 1.

TABLE 1. EXAMPLES OF TYPES OF NUCLEAR AND OTHER RADIOACTIVE MATERIAL

Type of material	Examples	
Nuclear material	Pu U-233	U-235 U-238
Medical radionuclides	C-14 Co-57 Ga-67 I-123	I-125 I-131 Tc-99m Tl-201
Industrial radionuclides	Am-241 Ba-133 Cd-109 Cf-252	Co-60 Cs-137 Ir-192 Sr-90

2.2. The IAEA Incident and Trafficking Database (ITDB)[2] contains information, reported voluntarily by States, on the unauthorized possession, theft or loss of, or other unauthorized activities involving nuclear and other radioactive material. From January 1993 to December 2013, 2477 confirmed incidents were reported to the ITDB. Of these confirmed incidents, 424 involved unauthorized possession and related criminal activities (16 of which involved high enriched uranium or plutonium), 664 involved the theft or loss of nuclear or other radioactive material, and a total of 1337 cases involved other unauthorized activities and events. An incident may belong to more than one of the types mentioned, for example the theft and subsequent attempted sale of a radioactive source. Accordingly, the sum of the incidents in the groups can differ from the total number of incidents. In 69 cases, the reported information was insufficient to determine the category of the incident.

2.3. The level of reporting indicates that, despite the existence of national nuclear security infrastructures, there are still incidents involving nuclear and other radioactive material out of regulatory control — whether unintentionally, such as through loss, or intentionally as a result of criminal acts, such as theft. Given this information, there is a need for States to develop the capability to prevent, detect and respond to any event involving nuclear or other radioactive material that has nuclear security implications. Events such as these are referred

[2] See http://www-ns.iaea.org/security/itdb.asp.

to as nuclear security events [5]. A nuclear forensic examination may be an important component of the response to a nuclear security event.

NUCLEAR FORENSICS AS A PREVENTIVE MEASURE

2.4. Lessons learned from the investigation of a nuclear security event may be incorporated into nuclear security measures, improving them and thereby aiding in the prevention of future nuclear security events. For example, nuclear forensic findings may determine that material has been removed from a facility or site previously deemed secure. Deficiencies may be identified in material accountancy or nuclear security systems, both at the facility and at the State level.

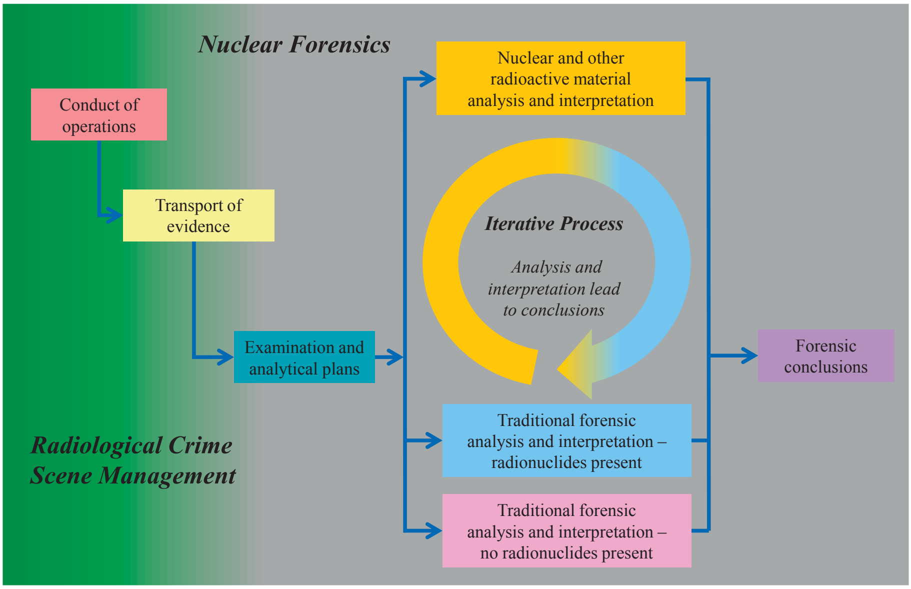
2.5. Knowledge that a State has nuclear forensic capabilities may also function as a deterrent to individuals or groups who may otherwise intend to divert or illicitly traffic nuclear or other radioactive material [4]. The success of nuclear forensics as a deterrent will be dependent on its credible implementation and demonstrated success in supporting investigations and subsequent successful legal proceedings that rely upon these findings.

NUCLEAR FORENSICS MODEL ACTION PLAN

2.6. The nuclear forensics model action plan shown in Fig. 1 provides generalized guidance on the conduct of a nuclear forensic examination and related activities that should be performed in the context of an investigation of a nuclear security event. The plan covers activities undertaken by the authorities requesting nuclear forensic examinations and by the laboratories that may be called upon to undertake the analysis and interpretation.

2.7. Nuclear forensic examinations are undertaken to respond to key questions posed by the investigative authority, which may relate to the intended use, history and origin of nuclear or other radioactive material involved in the nuclear security event under investigation. The questions posed by the investigative authority will be influenced by the nature of the nuclear security event and any related legal proceedings that may arise as a consequence of the investigation.

2.8. Nuclear forensic analysis and interpretation may lead to findings regarding the material associated with a nuclear security event. When combined with other aspects of the investigation, including traditional forensic findings, conclusions may be drawn about the associations between the material and people, places,



Note: Background shading indicates the transition from radiological crime scene management to nuclear forensics.

FIG. 1. Nuclear forensics model action plan: A process which supports an investigation of a nuclear security event.

events and production processes. States should recognize that although a nuclear forensic capability may not be used on a regular basis, it may play a significant role in the investigation of a nuclear security event.

NATIONAL FRAMEWORK FOR IMPLEMENTING A NUCLEAR FORENSIC CAPABILITY

2.9. All States should have a national response plan for nuclear security events to provide for an appropriate and coordinated response. As nuclear forensics can play a key role in the investigation of a nuclear security event, the nuclear forensics model action plan (see Fig. 1) should be incorporated into the national response plan to the extent possible.

2.10. States should ensure that the roles and responsibilities for nuclear forensics in relation to nuclear security events are clearly defined and that expertise, instrumentation and procedures are in place. There should also be the provision for the safe and secure storage of seized nuclear and other radioactive material, as well as the means to safely and securely transport such material from the scene of a nuclear security event to an evidence storage site. Such a storage site may be a laboratory capable of undertaking characterization of collected material or may be an interim location where seized material can be kept until it is transported to a designated nuclear forensic laboratory for analysis.

2.11. Development of a nuclear forensic capability within a State should begin by identifying existing capabilities, including facilities that are already established and relevant expertise that is already used for other purposes, and creating mechanisms for their use in an investigation. Relevant capabilities may exist, for example, at radiation protection institutions, radiochemistry or nuclear physics departments at universities, environmental monitoring laboratories, quality control laboratories of nuclear fuel cycle facilities, or security and defence establishments. Some States may be able to use experience or infrastructure created to help to verify compliance with, or adherence to, international treaties, including the Treaty on the Non-Proliferation of Nuclear Weapons [10] and the Convention on the Physical Protection of Nuclear Material [4] and the 2005 Amendment thereto [11] (which is not yet in force).

2.12. Where feasible, States may also establish a national nuclear forensics library that is under their control to enable a credible assessment of whether or not nuclear and other radioactive material encountered out of regulatory control is consistent with material produced, used or stored within the State. For further discussion on the development of a national nuclear forensics library, see paras 6.7–6.9.

2.13. International cooperation allows States to request, receive and provide nuclear forensic assistance to help to develop capabilities or as part of an investigation of a nuclear security event. Specialized analytical tools to characterize nuclear and other radioactive material may only be available in a few laboratories worldwide and may only be required for the investigation of a minority of nuclear security events. States without national capabilities to perform a full characterization of nuclear or other radioactive material or of evidence contaminated with radionuclides may choose to establish bilateral or multilateral agreements or arrangements with laboratories to provide additional nuclear forensic capabilities and/or facilitate assistance if the need should arise (see paras 8.7–8.10).

NUCLEAR FORENSICS IN RELATION TO INTERNATIONAL AND NATIONAL LEGAL INSTRUMENTS

2.14. The responsibility for nuclear security and, hence, for nuclear forensics rests entirely with each State. Currently, there is no single international legal instrument that fully addresses all aspects of a nuclear security infrastructure. The legal foundation for nuclear security includes a body of binding international legal instruments, such as conventions and treaties (which are binding on States Parties), and United Nations Security Council resolutions (which are binding on United Nations Member States), including those in Refs [4, 10–20], as well as recognized principles developed for the promotion and safe and secure use of nuclear technology. These international legal instruments have created obligations that require States, inter alia, to create offences in relation to specified intentional actions involving the misuse of nuclear and other radioactive material and to implement mechanisms for requesting, receiving and providing assistance. They also contain provisions on the return of these materials in defined circumstances and under certain conditions. Bilateral and multilateral legal instruments allow cooperation and the sharing of information and capabilities, and enhance international security.

2.15. Nuclear forensics supports the implementation of measures required by:

(a) The international legal framework for nuclear security and the manner in which the framework governs relationships between States, in particular cooperation and assistance with the investigation of nuclear security events that have transboundary implications;
(b) The national legal framework for nuclear security, in particular in support of a State’s legal actions related to a nuclear security event, including potential criminal prosecution.

2.16. States should ensure that a comprehensive legal and regulatory framework is established and maintained to support and empower competent authorities. The responsibilities to be defined and fulfilled include regulation, customs and border protection, the transport of material, policing and law enforcement, and the prosecution and adjudication of alleged offences involving nuclear or other radioactive material.

3. DEVELOPMENT OF THE FORENSIC EXAMINATION PLAN AND THE CORRESPONDING NUCLEAR FORENSIC ANALYTICAL PLAN

3.1. For the purposes of investigating a nuclear security event, once the preliminary on-scene assessment has been performed, including categorization of the nuclear or other radioactive material, a forensic examination plan should be prepared by the investigating authority in consultation with the relevant forensic laboratories, including designated nuclear forensic laboratories. Categorization is performed to identify nuclear security implications and the risk of the seized material to first responders, law enforcement personnel and the public. The forensic examination plan should describe the requirements of the examinations to be conducted in support of a potential criminal prosecution. In addition, the development of the forensic examination plan should consider any requirements to retain samples that may be requested by the court if the results of the investigation are used in legal proceedings.

3.2. One challenge encountered in conducting forensic examinations is establishing the sequence in which these examinations are to be performed. The sequencing of examinations conducted in both traditional forensic disciplines and nuclear forensics should ensure that critical information is obtained without unnecessary delay, and that the amount and quality of data derived from each sample are consistent with the request of the lead investigative authority. The presence of radionuclides adds to this challenge, since it may constrain the types of examination that can be undertaken and the locations where the examinations can occur. The sequencing of examinations should be described in the forensic examination plan.

3.3. The forensic examination plan should consider the needs of the investigation, the perceived value of the expected results to the investigation, the known or suspected losses of essential characteristics over time if examinations are delayed, and the national level procedures for the conduct of examinations in traditional forensic disciplines and nuclear forensics. In general, priority should be given to examinations where the results are capable of specifically identifying an individual person (e.g. DNA analysis or fingerprint examination) over those where the results are likely to identify only a group or class (e.g. shoe or tyre impressions, or the presence of a particular type of explosive). However, the presence of other investigative or intelligence information might enhance the value of class characteristic results, especially where narrowing the range of possibilities is critical to focusing the investigation.

3.4. In support of the forensic examination plan, each of the forensic laboratories involved should prepare an analytical plan in consultation with the lead investigative authority. This consultation is important to ensure that key requirements of the examination plan are not overlooked in the preparation of the analytical plans of each of the forensic laboratories.

DEVELOPMENT OF A NUCLEAR FORENSIC ANALYTICAL PLAN

3.5. A nuclear forensic analytical plan should be developed to describe specifically the types of analysis which will be performed in order to meet the requirements of the investigation and the sequencing of analyses that pertain to nuclear or other radioactive material, and evidence contaminated with radionuclides. An essential element of a nuclear forensic analytical plan includes characterization. Characterization is performed to determine the nature of the radioactive material and associated evidence (for the analytical tools and laboratory methods and techniques applicable to characterization, see paras 5.7–5.10 and 5.13–5.21, respectively). The nuclear forensic analytical plan should be prepared by the designated nuclear forensic laboratory or laboratories, with input and ultimately concurrence from the investigating authority, such that it meets the needs of the forensic examination plan and the investigation. The nuclear forensic analytical plan should be flexible and adaptable so that as new information is obtained through the investigation or through sample analysis, the requirements for the forensic examination may be revised. The nuclear forensic analytical plan can be modified as needed, with appropriate consultation and documentation.

Types of sample and analysis

3.6. The types of sample and analysis needed to answer the questions posed by the investigating authority should be considered when developing a nuclear forensic analytical plan. Table 2 provides some examples of the sample types that could be collected during an investigation of a nuclear security event, their potential forensic value and the examination requirements for such samples. Owing to the diverse nature of these types of samples and their specific requirements, it may not be possible to analyse all samples in the same physical location (e.g. part of a facility or laboratory), and this should be accounted for when developing the nuclear forensic analytical plan. For example, if trace radionuclide analysis is required, these measurements would not be conducted with or near the same experimental apparatus that performs bulk analysis of nuclear and other radioactive material.

TABLE 2. SAMPLE TYPES THAT COULD SUPPORT A NUCLEAR FORENSIC ANALYTICAL PLAN

Sample type	Potential forensic value	Examination requirements
Bulk nuclear or other radioactive material	Determine unauthorized possession Identify possible material origins Identify material process history Connect cases where the same material was discovered	Capability and infrastructure for handling and characterizing bulk radioactive and nuclear materials Expertise in nuclear fuel cycle technology to interpret results
Items contaminated with radionuclides	Identify places where nuclear or other radioactive material has been handled or processed Identify additional nuclear or other radioactive material that may have been previously handled at a location where bulk material was found Link those involved or suspected to the material	Experience with trace analysis of nuclear and other radioactive material and understanding of potential limitations of such samples and results (e.g. influence of environmental background) Ability to isolate and analyse small samples Expertise with traditional forensic analysis and interpretation
Biological samples (i.e. urine, blood, hair and tissue)	Identify individuals who have handled nuclear or other radioactive material Identify individuals who have received an external radiation dose Connect individuals to events involving nuclear or other radioactive material	Experience with bioassay analyses or blood dosimetry Health physics or radiobiology expertise to interpret results
Environmental or geological samples associated with the nuclear or other radioactive material	Determine possible smuggling routes or pathways through which the nuclear or other radioactive material was transported	Expertise with environmental analysis (i.e. minerals, dust and pollens) and interpretation of geological and geochemical data

Laboratory considerations

3.7. The laboratory undertaking the nuclear forensic analysis should operate under a quality assurance plan, which includes the sample chain of custody, validated analytical procedures, staff with demonstrated competencies, documented procedures, standard reporting forms and records management. The procedures for nuclear forensic analysis should include statements on the control of contamination or cross-contamination that explicitly apply to contamination with radionuclides. When developing a nuclear forensic analytical plan, the laboratory should identify procedures that will be followed and the quantity of material needed for each analysis, together with any foreseen deviations from documented procedures. The nuclear forensic analytical plan should also address any required interface with traditional forensic analyses, for example whether the nuclear forensic laboratory will assist in the collection of traditional evidence or the removal of radioactive contamination from materials prior to examination by a traditional forensic laboratory (see Section 4). Furthermore, the evidentiary value of nuclear forensic findings, even when based on analyses adhering to the relevant protocols and standards, may be severely compromised by deviating from the parameters and requested examinations set out in the forensic examination plan. Therefore, law enforcement experts should unambiguously communicate which methods and standards are acceptable for subsequent use in a court of law as well as the potential implications of any deviation from the nuclear forensic analytical plan.

SUBSAMPLING

3.8. For bulk nuclear and radioactive material samples, the entire sample may be larger than the sample size specified in the analytical plan. There may also be regulatory or technical limitations on the mass or activity that can be received and analysed at a laboratory. Therefore, it may be necessary to divide the material — a process referred to as subsampling — prior to shipment to the analysis laboratory. Given the potential heterogeneity of a sample, special subsampling protocols should be followed to ensure that subsamples are truly representative of the bulk material. Any limitations of these methods should be described in the analytical plan.

3.9. Techniques should be used for representative sampling that minimize the possibility of misleading results attributable to the heterogeneity of the evidence. In extreme cases, the need for representative samples might require analysis of individual particles; more commonly, bulk analysis is sufficient. When the amount of available material is limited, subsampling may not be required or may prove difficult. However, in such cases, the nuclear forensic analytical plan should prioritize the allocation of the material. In cases of limited material, it is important that all non-destructive analyses be performed prior to performing any analyses that will consume, or might alter, the sample characteristics. In addition, for small samples, trace and microanalytical techniques may be more appropriate than techniques optimized for larger amounts of material. Subsampling has the potential to introduce contamination or to compromise evidence, and appropriate precautions should be taken.

EVIDENCE DISTRIBUTION

3.10. Once the forensic examination plan and the nuclear forensic analytical plan have been established and any required subsampling has been conducted, the evidence should be distributed to the laboratories performing the analyses.

3.11. Forensic samples should be transported to laboratories using methods that maintain the chain of custody (e.g. the use of sealing devices or tags). In order to minimize the risk of unintended changes to the evidence during transport, the possible effects of the transport conditions (i.e. temperature, humidity or vibration) should be considered and may need to be addressed. The transport of nuclear and other radioactive material should be carefully planned, and individuals should be available with expertise in the transport of hazardous material, especially radioactive material. In addition, reliable and sustained communication between the shipper and receiver should ensure that the necessary procedures are followed for delivering nuclear or other radioactive samples to a laboratory.

4. FORENSIC EXAMINATION OF EVIDENCE CONTAMINATED WITH RADIONUCLIDES

4.1. Examinations of physical and documentary evidence conducted in traditional forensic disciplines are a routine element of investigations conducted by investigating authorities. Examples of these disciplines include the study of fingerprints, genetic markers (i.e. nuclear DNA and mitochondrial DNA), shoe and tyre impressions, tool marks, explosive residues, firearm ballistics, paints and other chemicals, metallic features, documents and trace evidence (i.e. fibres, hairs and pollens), and forensic medicine. Additional information on these disciplines is given in Annex I.

4.2. The conduct of examinations in traditional forensic disciplines and nuclear forensic examinations should complement each other. Both yield results that might aid in determining whether linkages exist among people, places, events and processes, and whether those linkages are indicative of where regulatory control was lost. These results can prove especially useful where they permit these associations or where they allow certain nuclear or other radioactive material to be excluded from further consideration. The potential for radioactive material to be present as a contaminant on or in physical evidence presents a particular challenge for examinations conducted in traditional forensic disciplines.

CONTAMINATED EVIDENCE

4.3. Any evidence associated with a nuclear security event should be examined to determine whether or not it is contaminated with radionuclides. Evidence found to be free of radionuclides can be submitted directly for forensic examination once released by the competent authority, as there is no radiological hazard to people handling the evidence.

4.4. Special considerations should apply when evidence is known or suspected to be contaminated with radionuclides. The term ‘contaminated evidence’ connotes a different meaning for the forensic scientist and for the nuclear forensic scientist, and the term merits discussion.

4.5. In general forensic science usage, ‘contaminated evidence’ results from the direct or indirect transfer of extraneous material to a forensic sample or scene of a crime. This may also be referred to as ‘cross-contamination’. Evidence that is contaminated with extraneous material, and thus compromised, has limited value for investigative purposes and should be evaluated carefully.

4.6. In nuclear forensics, ‘contaminated evidence’ could refer to the presence of radionuclides on or within physical evidence. This is the intended meaning in this publication, and the term ‘evidence contaminated with radionuclides’ is used to clarify this meaning. The contamination of evidence with radionuclides may affect the manner and timeliness with which the evidence should be examined. Cross-contamination with radionuclides may alter the radionuclide signature that is the goal of the forensic examination. Therefore, in the context of nuclear forensics, the examination of ‘evidence contaminated with radionuclides’ is subject to special planning and procedures.

HANDLING EVIDENCE CONTAMINATED WITH RADIONUCLIDES

4.7. When conducting examinations using traditional forensic disciplines on evidence contaminated with radionuclides, two approaches are possible. The first approach involves the removal or separation of the radionuclides from the evidence prior to conducting any examinations. This is often referred to as ‘decontamination of evidence’. The second approach directly examines the evidence while it is still contaminated with radionuclides. Both approaches may require input from many different agencies, in particular from those outside the law enforcement community. For this reason, there may be a need for extensive consultation between the relevant experts for the development of the forensic examination plan and prior to the handling of evidence contaminated with radionuclides. Each approach offers certain advantages and suffers from certain disadvantages, which should be evaluated during the course of the investigation and are described in paras 4.8–4.13.

Decontamination of evidence that is contaminated with radionuclides

4.8. Radionuclides may be removed from evidence by physical or chemical processes as part of the decontamination step. Various techniques exist for this purpose, and the selection of the optimal one will depend on, among other factors, the form of the evidence, the form of the radionuclides present, the type of examination to be performed, and practices dictated by national or local considerations. The decontamination of evidence prior to conducting an examination in a traditional forensic discipline offers several advantages:

(a) The decontamination of evidence may subsequently permit closer contact between the examiner and the evidence, since the potential for exposure to radiation has been minimized.
(b) The examination of decontaminated evidence can be performed in a manner similar to that for evidence that has not been contaminated with radionuclides, eliminating any need to train and, where applicable, certify the people involved in radionuclide handling techniques.
(c) The need for specialized infrastructure to support the conduct of the examination is negated.

4.9. There are, however, some disadvantages associated with the decontamination of evidence prior to the conduct of an examination in a traditional forensic discipline, including:

(a) The radionuclides with which the evidence is contaminated might be evidence.
(b) The time and expert resources that are typically needed to remove the radionuclides may be considerable.
(c) The evidence may be altered in some manner that might render any findings inaccurate or degrade the feature that is the subject of the examination.
(d) Complete removal of the radionuclides will often not be achievable, and incomplete removal could, if not recognized, lead to uncorrected radiation effects on the evidence and/or inadvertent exposure of the examiners. Strict adherence to operating procedures to verify the decontamination of evidence alleviates the potential for unintended effects.
(e) The waste generated in removing the radionuclides will likely need to be managed without harm to the environment.

4.10. Research into the effects of different decontamination techniques on individual physical examinations has already been conducted [21]. This work highlights some conclusions regarding when it is appropriate to attempt decontamination of certain types of evidence. These conclusions, and further research, should be used to develop protocols for handling evidence contaminated with radionuclides. These protocols should be considered in advance of conducting an examination related to an investigation of a nuclear security event.

Examination of evidence contaminated with radionuclides

4.11. The examination of evidence contaminated with radionuclides may be conducted without decontamination. This approach has several advantages, including:

(a) Minimizing the possible loss or degradation of features important to the examination that might have been caused by the process used to decontaminate the evidence;
(b) Expediency of the examination, which can commence immediately upon receipt of the evidence (assuming the availability of qualified personnel, appropriate equipment and instrumentation, and a written analytical plan).

4.12. However, directly examining physical evidence contaminated with radionuclides carries certain disadvantages, including:

(a) The radiation exposure to personnel, which may be reduced by appropriate radiation safety measures that take account of international safety standards [1], but is unlikely to be completely eliminated;
(b) The need for specialized facilities and personnel trained to perform examinations in traditional forensic disciplines on evidence contaminated with radionuclides, including dedicated equipment and instruments at these facilities;
(c) The need to validate the application of traditional forensic science techniques to evidence contaminated with radionuclides in facilities not typical for forensic examinations;
(d) The potential for prolonged exposure to radiation to degrade or otherwise impact the forensic quality of the evidence. Research has been initiated to determine whether such exposure has any effects and, if so, whether these effects might be mitigated [22]. This should be done in advance of the investigation.

Determination of the appropriate approach to decontamination

4.13. The decision as to whether to attempt the decontamination of evidence or to conduct examinations on the evidence while it is still contaminated with radionuclides should be addressed in the forensic examination plan and will be dependent on factors such as:

(a) The nature of the evidence, the contaminant and the examinations to be performed;
(b) Availability of relevant resources for the conduct of the examinations;
(c) Information so far obtained through investigative or intelligence methods, and from any related examinations that have been performed;
(d) National policies and procedures for responding to nuclear security events.

5. NUCLEAR FORENSIC LABORATORY ANALYSIS

5.1. Based on the categorization and the requirements of the forensic examination plan, characterization of the nuclear or other radioactive material may be necessary. This characterization should take place in a designated nuclear forensic laboratory. Prior to commencing the analysis, the laboratory should develop a nuclear forensic analytical plan, which will be agreed to by the investigative authority, as discussed in Section 3.

CHARACTERIZATION

5.2. The goal of characterization is to determine the physical characteristics, chemical and elemental composition, and isotopic ratios of the nuclear or other radioactive material, which is achieved through a range of relevant analyses, and may include identifying major, minor and trace constituents, as necessary. Characterization does not typically include analysis using traditional forensic disciplines, nor does it include interpretative steps, such as the modelling of nuclear reactor processes possibly related to material origin or the identification of the possible origins. As such, the characterization will take less time than full interpretation.

DESIGNATED NUCLEAR FORENSIC LABORATORY

5.3. Designated nuclear forensic laboratories are laboratories that have been identified by a State as being capable of accepting and analysing samples of nuclear and/or other radioactive material for the purpose of supporting nuclear forensic examinations. The criteria and decision process to identify and then designate a nuclear forensic laboratory are the responsibility of each State. Once the investigating authority has determined that a nuclear forensic examination is required, the evidence should be sent to a laboratory that has been identified and designated as being prepared and equipped to receive the samples (nuclear and other radioactive material, evidence contaminated with radionuclides or a combination thereof) and to analyse them using the necessary combination of analytical techniques. Communication between the investigating authority and the laboratory should commence as early as possible following the response to the nuclear security event so that laboratory requirements and capabilities can be communicated, and planning and preparations for sample receipt and analysis can be made through the development of the forensic examination plan and the nuclear forensic analytical plan. When transporting the evidence to, and admitting evidence at, a designated nuclear forensic laboratory, due regard should be paid to evidence handling, including that the appropriate chain of custody arrangements for sample handling is in place (see para. 3.11).

5.4. The extent of capabilities available at designated nuclear forensic laboratories is likely to vary from State to State. Some States may not have a designated nuclear forensic laboratory of their own and will rely on bilateral or multilateral assistance for characterization. Other States may have established designated laboratories for undertaking some aspects of characterization or for some types of material, with plans in place to request assistance for specialized techniques. Only a few States worldwide have laboratories possessing a full complement of the nuclear forensic analytical tools and techniques that might be needed. Each State should have a thorough understanding of its own capability and should ensure that it is prepared for any eventuality, including having arrangements in place to request, receive or provide assistance (as appropriate) to undertake nuclear forensic analysis in support of an investigation of a nuclear security event.

5.5. The State should ensure that any designated nuclear forensic laboratory is capable of undertaking a nuclear forensic examination and that they have validated analytical methods, staff with demonstrated competencies and documented procedures. Accreditation of the laboratory to an internationally recognized quality standard is advantageous (e.g. ISO 9001:2008 [23], ISO 14001:2004 [24], ISO/IEC 17025:2005 [25], OHSAS 18001:2007 [26]). In addition, the designated nuclear forensic laboratory should have the necessary authorization to receive nuclear and other radioactive material and, where possible, have the ability to handle large amounts of material (in terms of mass and activity) if necessary, while still being able to analyse trace constituents. Designated nuclear forensic laboratories may possess glove boxes or, for cases where highly radioactive samples are anticipated, hot cells. The designated nuclear forensic laboratory should also have appropriate laboratory facilities and operational procedures to minimize the risk of cross-contamination between samples.

5.6. The designated nuclear forensic laboratory should apply appropriate physical protection measures and, where necessary, procedures for the accounting and control of nuclear material. The laboratory should also be fully compliant with the requirements for facilities storing and handling radioactive material [1] and, if necessary, corresponding requirements for the storage and handling of hazardous material. The laboratory should have appropriate security measures in place to ensure the integrity of the chain of custody and to protect any sensitive information associated with the nuclear forensic examination.

ANALYTICAL TOOLS

5.7. The nuclear forensic scientist has a wide array of tools to use for measuring the properties of nuclear and other radioactive material. Annex II provides descriptions of many of the analytical techniques used for characterization. These individual tools and techniques fall into three broad categories: imaging, bulk analysis and microanalysis.

5.8. Imaging tools produce high magnification images or maps of the material surface and provide information on sample heterogeneity and microstructure. Assessing the degree of sample heterogeneity is important. If the material is heterogeneous, bulk analysis will not produce results that are representative of those that would be obtained from smaller samples. Imaging can also reveal spatial and microstructural features (e.g. texture and grain structure), which may provide information about the thermodynamic or mechanical processing of the material.

5.9. Bulk analysis tools allow characterization of either an entire sample or a portion of the sample to determine the average properties of the material. The characterization of nuclear or other radioactive material may include measurements of physical characteristics, chemical and elemental composition, and isotopic ratios (see paras 5.13–5.20). If the goal of bulk analysis is to provide information on trace constituents of the material, it is necessary to have sufficient material for accurate and precise measurements. The presence or absence of trace constituents and their corresponding concentrations are often important for providing information about the manufacturing process.

5.10. If imaging analysis confirms that the sample is heterogeneous, microanalysis tools that can chemically identify and/or quantitatively analyse very small samples (generally <1 mg) can characterize the individual constituents of the material. Microanalysis tools also incorporate surface measurements, which can identify trace surface contaminants or can measure the composition of thin layers or coatings, which could provide important information for the interpretation.

SEQUENCING OF TECHNIQUES AND METHODS

5.11. Many of the analytical tools used in the analysis of nuclear or other radioactive material are destructive techniques (i.e. the sample is consumed during the preparation and analysis). Therefore, the proper selection and sequencing of analytical techniques is critical and should be defined in detail in the nuclear forensic analytical plan. The sequencing of analytical techniques should be based on the questions to be answered from the investigating authority according to the forensic examination plan, taking into account the amount of sample available for analysis, information already available and the potential signatures (physical, chemical, elemental and isotopic) that might support precise interpretation.

5.12. The Nuclear Forensics International Technical Working Group (ITWG) — an association of nuclear forensic practitioners — has developed recommendations on the sequencing of techniques to provide the most valuable information as early as possible in the analysis process. The recommendations are based on expert opinion and on experience gathered from three collaborative analytical exercises undertaken by ITWG member laboratories; these exercises are discussed further in Annex III. Table 3 presents the ITWG recommended sequence of analyses, arranged by techniques that could be performed within 24 hours, 1 week or 2 months from the sample's arrival at the designated nuclear forensic laboratory (see Annex II for descriptions of frequently used techniques). Some techniques can also be used at a later time to achieve more precise analytical results using longer measurement times. The use of such timescales to complete material analyses may also guide the expected intervals of reporting results, corresponding to the analytical intervals of 24 hours, 1 week and 2 months, depending on the situation. The duration of the characterization process will depend on the workload of the laboratory, the nature of the sample and the requirements of the investigation detailed in the forensic examination plan, but with a goal of completion within two months after receiving a sample.

SAMPLE ANALYSIS

5.13. After the sample arrives at the nuclear forensic laboratory, the material should first be analysed under controlled conditions with high resolution gamma ray spectrometry. The analysis may confirm or modify the results of the on-scene analysis, and may also provide new information, such as the total amount of nuclear or other radioactive material present.

5.14. The characterization of nuclear or other radioactive material may include measurement of physical characteristics, chemical and elemental composition, and isotopic ratios, as described in paras 5.15–5.21 and summarized in Table 3.

TABLE 3. LABORATORY METHODS AND TECHNIQUES WITH TYPICAL TIMESCALES FOR COMPLETION OF ANALYSES

Technique/method	Conducted within		
	24 hours	1 week	2 months
Radiological	Dose rate (α, β, γ, n) Surface contamination Radiography		
Physical characterization	Visual inspection Photography Weight determination Dimensional determination Optical microscopy Density	Microstructure, morphology and other physical characteristics SEM X ray diffraction	Nanostructure, morphology and other physical characteristics TEM
Isotopic analysis	HRGRS	TIMS ICP-MS	SIMS Radioactive counting techniques
Radiochronometry	HRGRS (for Pu)	TIMS ICP-MS	HRGRS (for U) Alpha spectrometry
Elemental/chemical composition	X ray fluorescence	ICP-MS Chemical assay FTIR spectrometry SEM/X ray spectrometry IDMS	GC–MS
Traditional forensic science disciplines	Collection of evidence associated with traditional forensic disciplines		Analysis and interpretation of evidence associated with traditional forensic disciplines

Note: FTIR — Fourier transform infrared; GC–MS — gas chromatography–mass spectrometry; HRGRS — high resolution gamma ray spectrometry; ICP-MS — inductively coupled plasma mass spectrometry; IDMS — isotope dilution mass spectrometry; SEM — scanning electron microscopy; SIMS — secondary ion mass spectrometry; TEM — transmission electron microscopy; TIMS — thermal ionization mass spectrometry.

Physical measurements

5.15. The first step in sample characterization usually involves visual inspection of the material, which may include documenting or photographing specific markings (e.g. serial numbers or product logos), colour, size and shape. In the case of bulk solid items, the weight, density, activity and basic features of microstructure (grain size, texture and inclusions, as applicable), along with the visual inspection results, may reveal sufficient information at the macroscopic scale to identify the sample. For example, in the case of nuclear reactor fuel pellets, the exact dimensions and geometry of a fresh nuclear fuel pellet are often unique to a given manufacturer. For sealed radioactive sources, the size, activity and the form of encapsulation often provide insights regarding the manufacturer of the source.

5.16. At the microscopic scale, microstructural features enable more detailed comparisons of materials. For example, the grain size distribution and the grain structure of uranium oxide fuel pellets can provide information about their production processes. In the case of powder or swipe samples, particle morphology may exhibit distinguishing features that result from different production processes.

Chemical and elemental measurements

5.17. The chemical form of nuclear material (e.g. metal, oxide or an intermediate product, such as ammonium diuranate) or other radioactive material is an important indicator that may reveal information about the production process of the material, and may provide insight into its original intended use. In the case of a uranium intermediate product, the compound can give an indication about the process used to produce the material and, as a result, narrow the number of possible production facilities.

5.18. Besides the nuclear or other radioactive material of interest, many other elements may be present in the material under investigation, sometimes at concentrations exceeding that of any radionuclide. Such elements may have been added intentionally to achieve certain material properties (e.g. erbium and gadolinium to control nuclear fuel reactivity). Unintentional chemical impurities may also be present as a result of residual elements from the initial feed materials or residuals from chemicals added during the production process (e.g. acid residues), as well as from corrosion or abrasion of vessels and pipe work. If these elements are present at trace levels, they are referred to as impurities, and the range and concentrations of such elements may be highly characteristic of particular processes, raw materials or facilities. Measurements of these elements may, therefore, be important for an examination, as they can provide information not only on the intended lawful use, but also on the source material or on the type of production facility.

Isotopic measurements

5.19. Isotopic measurements are conducted to determine the isotopic abundance of elements present in the nuclear or other radioactive material. The isotopic abundance provides information about the material history and its intended use, for example whether the nuclear material is of natural isotopic composition or, if it has been enriched in fissile isotopes or reprocessed, whether that was likely to have been used as nuclear fuel or potentially in a nuclear explosive. Besides the major fissile isotopes (^{239}Pu and ^{235}U), the relative concentrations of minor isotopes of plutonium and uranium (e.g. ^{240}Pu, ^{238}Pu and ^{236}U) may reveal any previous irradiation history of the nuclear material.

5.20. Radiochronometry uses isotope measurements to determine the amount of time that has elapsed since the nuclear or other radioactive material was last chemically purified (i.e. the time when daughter nuclides from the decay of their parent radionuclides were separated from the parents). The concentration of radioactive decay products of plutonium and uranium, referred to as the daughter products (e.g. ^{241}Am and ^{230}Th), can be measured and compared with the concentration of the parent isotope to determine the age of the separated nuclear material. Radiochronometry is also applicable to radioisotope sources such as those containing ^{137}Cs, which decays to stable ^{137}Ba.

5.21. Besides the isotopic composition of the fissile elements and their decay products, the presence and isotopic composition of other elements can provide information about the origin of a sample, based on known natural isotopic variations worldwide. The isotope ratios of such elements in a sample can be indicative of the process or the production location (e.g. ^{18}O/^{16}O ratio) or of the feed material (e.g. ^{87}Sr/^{86}Sr ratio and ^{143}Nd/^{144}Nd ratio).

6. NUCLEAR FORENSIC INTERPRETATION

6.1. Once analyses have been performed, it may be necessary to use additional expertise to interpret the analytical results and to formulate nuclear forensic findings in response to the forensic examination plan. This expertise may need to be obtained from outside the laboratory that performed the measurements. Nuclear forensic interpretation is the process of comparing and associating sample characteristics with existing information pertaining to types of material, and origins and methods of production of nuclear or other radioactive material, or with previous cases involving similar material. Nuclear forensic interpretation provides the context, explanations for the analytical results, and the basis of the nuclear forensic findings.

PROCESSES OF INTERPRETATION

6.2. Nuclear forensic signatures are a set or sets of data characteristics of a given sample of nuclear or other radioactive material that may enable the sample to be identified as being consistent with, or as not being consistent with, particular nuclear or other radioactive material used, produced or stored in a State by way of either exclusion or inclusion. These signatures may help to identify the processes that created the material and its subsequent history.

6.3. Reference signatures for processes and facilities throughout the nuclear fuel cycle, as a basis for interpreting analytical results from samples, are established using both empirical approaches, involving results from previous analyses of nuclear and other radioactive material, and modelling approaches based on the chemistry and physics of nuclear fuel cycle processes. Knowledge of analytical science can guide the selection of the appropriate methods to verify the presence or absence of specific nuclear forensic signatures.

6.4. Nuclear forensic interpretation involves comparison of the results from the analyses of the sample in question with information on the corresponding characteristics of existing or known materials. In general, a single signature of a material (e.g. one isotopic measurement) is usually not sufficient to identify a specific sample uniquely from known classes of similar materials. Unlike traditional fingerprint examination, for example, it may be impractical in the absence of an archive to rely on the comparison of an analysis of a single sample in question to an analysis from existing or known samples. However, combinations of signatures, such as isotopic measurements, impurities and microstructure, when used together, can provide increased confidence in associating a specific sample with data representing a known class of similar material. The use of signature combinations may also enable exclusion — the conclusion that a specific sample is not comparable with known data classes of material — which can also be valuable for nuclear forensic interpretation.

6.5. Resources that may assist in comparisons with information on known classes of material include a national nuclear forensics library or associated databases containing information on nuclear and other radioactive material used, produced or stored within the State, augmented by subject matter expertise to aid in the interpretative process. Archived samples may be reanalysed for comparison.

6.6. As an example, Table 4 lists some information that may be necessary to answer questions about a plutonium sample and the signatures used to obtain the information.

TABLE 4. EXAMPLES OF RELEVANT RADIONUCLIDE SIGNATURES IN PLUTONIUM

Information required	Signature
Chemical processing date	Ingrowth of daughter isotopes
Chemical processing techniques	Residual elements (U/Pu ratio)
Use as a source of radioactive decay energy	Activity of Pu isotopes (^{238}Pu)
Neutron spectrum and burnup of the fuel in the reactor	Pu isotope ratios (e.g. ^{240}Pu/^{239}Pu)

DEVELOPMENT OF A NATIONAL NUCLEAR FORENSICS LIBRARY

6.7. A national nuclear forensics library is one tool available for use in a nuclear forensic interpretation. A library and reference databases may contribute to a State’s ability to assess whether or not material encountered out of regulatory control is consistent with nuclear and other radioactive materials produced, used or stored within the State [5]. A national nuclear forensics library is an administratively organized collection of information on nuclear and other radioactive material produced, used or stored within a State, which may come from different and diverse sources. A library may facilitate comparisons of measured characteristics of nuclear and other radioactive material with signatures of classes of known materials (e.g. physical characteristics, chemical and elemental composition, and isotopic ratios).

6.8. Where a national nuclear forensics library exists for these purposes, it should be established, maintained and controlled by the State, and be commensurate with the size and complexity of the State's holdings of nuclear and other radioactive material.

6.9. In order to foster such comparisons, a national nuclear forensics library should be developed, where practical, using a common conceptual organizing framework.

KNOWLEDGE OF NUCLEAR FUEL CYCLE PROCESSES AND RADIOACTIVE SOURCE MANUFACTURING

6.10. The characteristics reflected in nuclear forensic signatures are imparted to nuclear and other radioactive material at various points in their history, including during their manufacture. Understanding how these signatures are created, persist and are modified during material production processes is critical for nuclear forensic interpretation. As a result, knowledge of nuclear fuel cycle processes and the manufacturing of radioactive sources are fundamental for the effective interpretation of laboratory measurements. Such knowledge is obtained from subject matter expertise, usually resident in a variety of international, national and non-governmental entities.

6.11. Modelling or simulation of nuclear fuel cycle or material production processes can predict how signatures are imparted to nuclear and other radioactive material during its production. Modelling may also improve the understanding of phenomena that create or modify signatures, as well as those that enable the persistence of signatures. Knowledge gained through process modelling helps to provide the context for subsequent laboratory measurements and may also help to reveal new signatures.

6.12. Comparing the results of material characterization with signature combinations from process information (e.g. isotopic measurements, impurities and microstructural features) provides an understanding of how the material may have been made and its original intended use. Conversely, such comparisons also enable production processes and intended uses to be excluded from consideration if no association is established between characterization results and specific signature combinations.

Archived material

6.13. Comparative analyses of archived nuclear and other radioactive material, including seized material, can greatly contribute to confidence in nuclear forensic findings. These analyses allow the nuclear forensic expert to establish connections between the material and the processes used in its production or manufacture. As new signatures are discovered through the use of new analytical methods, it becomes increasingly important that archived data be accompanied by archived material. Depending on the half-life of the radionuclides of significance in a particular material, the archived material may be reanalysed using new analytical methods and the resulting data evaluated for the presence or absence of the newly discovered signatures. Sample archives maintained by operators, producers, regulators, environmental laboratories and others may include previously analysed samples of material, such as reactor fuel, quality control samples and industrial radioactive sources.

Open literature

6.14. Many of the basic nuclear processes are documented in textbooks, reports and journal articles in the open literature. The IAEA nuclear information web site, for example, has a number of databases that document publicly available information about nuclear facilities around the world.[3]

Closed literature

6.15. Proprietary or classified information may only be documented in ‘closed’ literature. Companies may be willing to share proprietary information with competent authorities or national laboratories after the execution of an appropriate non-disclosure agreement. Nuclear institutes, relevant ministries and national laboratories may be able to access classified literature within their own State, but they are unlikely to have permission to access classified documents from other States.

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[3] See http://nucleus.iaea.org.

DEDUCTIVE AND ITERATIVE PROCESS

6.16. Nuclear forensic analysis and interpretation involve a deductive and iterative process, as depicted in Fig. 2. Implementing the analytical plan produces results that can be compared with information on existing or known materials, and such comparisons lead to interpretation, which puts the analytical results into context. The comparative process involving analytical results and known material information is iterative because each successive comparison may provide new information that can identify further analyses or comparisons that, in turn, may uncover additional signatures that will help to identify the material more precisely. This comparative process may also be deductive because it can be used to progressively exclude particular processes, locations or other origins as possible sources of the material. For example, comparisons of analytical results from seized nuclear material with known production processes will identify likely production processes that could have made the seized material, as well as those processes that could not have made the seized material. Additional comparisons with other existing production processes or analytical measurements will serve

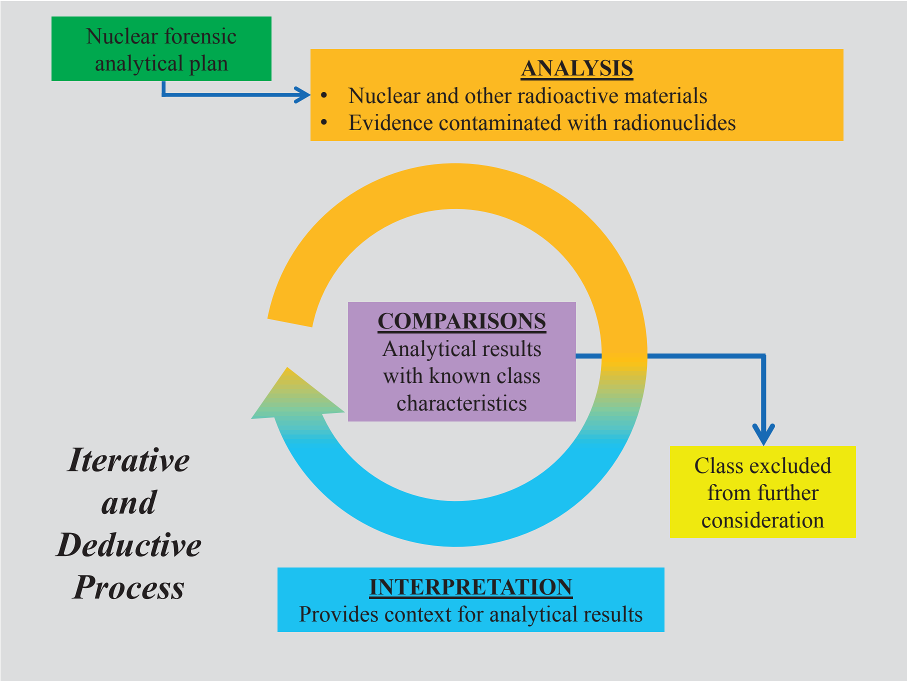

FIG. 2. Nuclear forensic analysis, comparisons and interpretation: An iterative and deductive process to provide context for analytical results.

to narrow the list of likely production processes responsible for the production of the seized material.

6.17. As results of the analyses are received and interpreted, they may yield information that law enforcement personnel might use for the purposes of the investigation. There may be times when a nuclear forensic examination cannot definitively conclude how a material was made or where it may have originated, but may still be able to exclude processes that are inconsistent with the evidence concerning the material's production history. Both actions — generating investigative leads and excluding certain scenarios — serve to narrow the focus of the investigation. Finally, the results of investigative activities undertaken by law enforcement can aid in uncovering additional evidence that might identify links between the nuclear or other radioactive material and people, places, times, events and production processes of interest.

7. NUCLEAR FORENSIC FINDINGS

7.1. Nuclear forensic findings are the products of nuclear forensic analysis and interpretation. The findings may support law enforcement investigations, regulatory inquiries and policy making, and assist other relevant stakeholders in improving nuclear security and preventing future nuclear security events. The key questions posed in all scenarios are typically the same:

— What type of material is involved?
— What is the possible origin of the material?
— What are the probable methods of production?

CONFIDENCE IN FINDINGS

7.2. In general, confidence in analytical results depends on three factors: (i) validated methods; (ii) certified reference materials; and (iii) demonstrated competencies. The use of validated methods ensures that the analysis is suitable for the material and capable of measuring the analyte(s) of interest. The use of certified reference materials ensures that measurements are benchmarked against known and certified values. Validated methods and certified reference materials provide confidence in the findings by demonstrating a measure of reliability in the procedures by which they are obtained. The use of demonstrated competencies provides confidence in the individual(s) performing the analyses.

7.3. Confidence in interpretation relies on the articulation of the uncertainties in the results of individual analytical measurements, in the results of iterative comparisons of analytical results with existing class information, and in the consideration of alternative explanations in interpreting the results of those comparisons. Taken together, these three factors allow the interpretation and its associated confidence level to be defended through a demonstrated understanding of their basis.

7.4. It is essential that any nuclear forensic analyses and interpretations are defensible because nuclear forensic findings may be used in legal proceedings or to identify nuclear security vulnerabilities. Strict adherence to chain of custody procedures throughout the investigation and implementation of quality assurance and quality control procedures at the laboratories contribute to confidence in the analytical results. In addition, an analytical plan that uses multiple results to converge on specific findings (e.g. associating or excluding certain classes of material) increases the confidence in the findings and conclusions.

COMMUNICATION OF FINDINGS

7.5. All nuclear forensic findings should be communicated in a written report in a timely manner. The reports may be presented in the form of a scientific report or may need to be in a specified standard format required by the national authority or the lead investigative agency. Sensitive information included in these reports will need to be identified and protected accordingly.

7.6. The level of confidence attached to the results and their interpretation should be clearly communicated in accordance with the requirements set out in the forensic examination plan. In order to advance the investigation, the nuclear forensic findings will be combined with findings and information from other disciplines, including other forensic science disciplines and information provided by other authorities, such as national security services. The results of the nuclear forensic analysis and the confidence levels associated with the findings should be conveyed in a manner that meets the needs of the investigation.

7.7. In the time sensitive environment of a nuclear security event, there may be a need to obtain reliable initial information as rapidly as possible. Nuclear forensic findings will be requested by investigators, as well as decision makers and other officials, well before full analysis and interpretation of measurements are completed. Ideally, a method for articulating the confidence levels associated with preliminary reports should be in place. To address information requests from investigators and decision makers, a summary of preliminary nuclear forensic findings should be developed that reports the key findings along with key assumptions, the confidence levels for these findings and any alternative explanations that remain credible in the light of the information available to date.

7.8. To assist with expectation management concerning the reporting of results, the forensic examination plan should outline the specific form and timeframes in which findings should be communicated. Reports on the status and findings of nuclear forensic examinations may be issued periodically, both during and after the nuclear security event. The preparation of reports may follow the 24 hour, 1 week and 2 month timescales typical for completion of analyses, as outlined in Table 3. A final report should also be issued after the examination has been concluded. The final report should identify all data and other information used in the assessment, and should describe the assumptions made and the rationale for the findings presented. Any data or information that are not consistent with the findings should also be identified in the report, along with the rationale for excluding or discounting that information or giving precedence to other information.

AFTER ACTION REVIEW

7.9. Following the conclusion of a nuclear forensic examination and completion of all related legal proceedings, an ‘after action review’ may be useful for assessing which of the various analyses and procedures performed during the course of the investigation met expectations and which failed to meet expectations. The purpose of an after action review is not to focus exclusively on the shortcomings, but also to understand what contributed to the success of those actions that met or exceeded expectations. Conducting an after action review provides an opportunity to learn from experience and to provide feedback into the processes used to plan for and carry out nuclear forensic examinations in the future.

7.10. Given the general need to improve how nuclear forensic analyses are conducted, experts in the field of nuclear forensics are encouraged to share with their counterparts in other States any lessons learned from actual nuclear security events or from the conduct of exercises, where considerations of confidentiality permit.

8. INTERNATIONAL COOPERATION AND ASSISTANCE

8.1. International cooperation and assistance may contribute in advance of, during or following a nuclear security event. The scope of international cooperation and assistance in nuclear forensics includes a range of activities that span raising awareness, research and development, international assistance and capacity building.

INTERNATIONAL COOPERATION

8.2. A number of international organizations, groups and initiatives promote awareness of the importance of nuclear forensics and provide, on request, various forms of nuclear forensic support. The Global Initiative to Combat Nuclear Terrorism (GICNT), INTERPOL and the Nuclear Forensics International Technical Working Group (ITWG) offer various forms of training, guidelines and assistance. States may also choose to cooperate bilaterally or multilaterally in the field of nuclear forensics. In addition, some States have national programmes that can provide support to international partners.

Global Initiative to Combat Nuclear Terrorism

8.3. The GICNT is a voluntary partnership of States working to strengthen global capacity to prevent, detect and respond to the shared threat of nuclear terrorism. Currently, the GICNT Nuclear Forensics Working Group is assisting the political leadership in partner States to build domestic capacity in nuclear forensics by developing tools to raise awareness of nuclear forensics, foster intergovernmental relationships, conduct joint exercises and promote best practices for nuclear forensics [27].

International Atomic Energy Agency

8.4. The IAEA provides support to States in their efforts to establish and maintain an effective nuclear security infrastructure, including nuclear forensic capabilities. This is accomplished through international guidance issued by the IAEA Nuclear Security Series publications, including the present guidance on the application of the model action plan, and through measures to assist States, upon request, in applying that guidance. Further measures include training on nuclear forensic awareness, radiological crime scene management and nuclear forensic methodologies, and coordinated research projects [28].

INTERPOL

8.5. INTERPOL is an international organization engaged in supporting national police organizations in preventing and combating criminality, including radiological and nuclear terrorism. Its primary activity is to facilitate the exchange of information, including investigative information, among its global membership. In addition, INTERPOL conducts intelligence analysis and delivers training (e.g. on managing a radiological crime scene), and is able to provide operational support during a nuclear security event.

Nuclear Forensics International Technical Working Group

8.6. The ITWG is an informal working group of nuclear scientists, law enforcement personnel, first responders and nuclear regulatory experts that collectively form a body of nuclear forensic practitioners [29]. The objective of the ITWG is to advance the discipline of nuclear forensics by developing effective technical solutions and providing advice to national and international authorities on how best to respond to criminal and intentional unauthorized acts involving nuclear or other radioactive material. The ITWG develops technical guidelines, organizes collaborative material analysis exercises as well as tabletop exercises, and promotes outreach internationally. Additional information is available on the ITWG web site.[4]

NUCLEAR FORENSIC ASSISTANCE DURING THE INVESTIGATION OF A NUCLEAR SECURITY EVENT

8.7. Assistance during the investigation of a nuclear security event may be facilitated through international organizations or through bilateral/multilateral agreements and arrangements. Assistance may include support for evidence collection, optimizing methods of analysis, conducting nuclear forensic analysis, improving confidence in the analyses, collecting data to help in nuclear forensic interpretation or providing other types of information upon request.

8.8. When formulating a request for assistance, the requesting party should consider the following points when drafting its request (not listed in order of priority):

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[4] See http://www.nf-itwg.org.

(a) Whether the request is in response to a specific event in which nuclear or other radioactive material has been found out of regulatory control, or is part of a strategy to prepare for such events [30, 31];
(b) Whether it is to be considered a sensitive matter and therefore requires protection of sensitive information;
(c) Whether the requesting State will permit the sharing of results by the assisting party with third parties or others not directly involved in providing the assistance and, if so, under which circumstances and how this sharing is to be accomplished;
(d) Whether the assisting party is requested to collect, package and transport the nuclear or other radioactive material from the territory of the requesting party to a facility in the territory of the assisting party in keeping with safety considerations, transport requirements and declarations concerning the import and export of nuclear and other radioactive materials;
(e) Whether the assisting party needs to adhere to a chain of custody and other related evidence handling requirements that prevail in the legal system of the requesting party;
(f) Whether the request requires ministerial level approval from the requesting and/or assisting parties and, if so, how these approvals will be obtained;
(g) Whether the assisting party may expect to be reimbursed for costs incurred in honouring the request or will be expected to absorb such costs;
(h) Whether there may be a need to provide testimony by experts from the assisting party and, if so, under what conditions such testimony might be needed (e.g. in person, in writing or via a remote communications link);
(i) Whether the return of nuclear or other radioactive material to the requesting party will be considered. With regard to this point, both the requesting and the assisting parties should be mindful of obligations arising from international legal instruments with regard to nuclear and other radioactive materials, such as those contained in the Convention on the Physical Protection of Nuclear Material [4], the International Convention for the Suppression of Acts of Nuclear Terrorism [12] and within safeguards agreements and relevant export control regulations.

8.9. One approach to facilitate a request for assistance is to develop a statement of work, or similar document, to be agreed between the requesting party and the assisting party or parties. It could address, as appropriate, the issues listed above and specify the expectations with regard to timeliness and means of reporting, the development of an analytical plan (if required by the nature of the request), the manner of reporting results and the analyses to be used. A less formal approach might be appropriate when the request does not require laboratory analyses, such as a request to share best practices in nuclear forensics, to offer expert advice on the conduct of nuclear forensic related exercises or to assist with plans for enhancing national capacities for nuclear forensics.

8.10. As such arrangements involve multiple and complex issues, it is advisable that, within its national response plan, each State defines and includes the arrangements that may be needed in an actual nuclear security event in relation to the provision of, or request for, international assistance.

9. NUCLEAR FORENSIC CAPACITY BUILDING

9.1. Developing and sustaining a nuclear forensic capability is a State's responsibility. Elements such as infrastructure, legal and regulatory frameworks, operations, human capital, and specialized equipment and knowledge are critical for an effective nuclear forensic capability.

9.2. Strategies for developing, testing and sustaining nuclear forensic capability and capacity are essential to enable a suitable response to a nuclear security event. These approaches will include building awareness of nuclear forensics for stakeholders at all levels, appropriate training of existing and future personnel, exercising response actions, designing research and development programmes, effective knowledge management in anticipation of future requirements, and effective education in nuclear science to foster and sustain capabilities (see Annex III for specific examples).

AWARENESS

9.3. A key element in developing a State's nuclear forensic capability is awareness of the contribution of nuclear forensics to the State's nuclear security infrastructure. Increasing awareness of nuclear forensics for all stakeholders within the State can help:

- To promote an understanding of nuclear forensics among facilitators and developers of a nuclear forensic capability;
- To clarify roles and responsibilities;
- To increase the knowledge of nuclear forensics applied to law enforcement investigations and nuclear security vulnerability assessments;

— To encourage the use of common terminology among different organizations and disciplines.

TRAINING

9.4. A State is responsible for ensuring that its national nuclear security infrastructure is supported by appropriately trained personnel. Technical training and human capital development should encompass the complexities of nuclear forensics as a component of preventive measures and as a capability for response. Training is an essential component of a sustainable programme in nuclear forensics by providing essential information on the requirements of an investigation of a nuclear security event, recommended methods for analysis and interpretation, and the role of nuclear forensics in a State's nuclear security infrastructure. Training may also be supported through international nuclear forensic partnerships.

9.5. Training should be tailored to the learning objectives required. For example, to be effective in communicating scientific results to law enforcement officials and policy makers or decision makers during a nuclear security event, it is important for nuclear forensic specialists to be trained to effectively convey this information to these audiences. Similarly, the IAEA has developed introductory training as well as training focused on specific technical analytical methodologies used in nuclear forensic laboratories.

EXERCISES

9.6. An effective nuclear forensic capability depends on collaboration between science and technology organizations, law enforcement agencies and other government agencies, both nationally and internationally. The development of collaborative and shared processes and mechanisms is essential for the continued development of nuclear forensic capabilities. The planning, execution and review of nuclear forensic exercises is a key component to bolster these capabilities.

9.7. Nuclear forensic exercises allow States to test and develop confidence in their response to a nuclear security event by allowing decision makers and personnel to practise performing their roles in a realistic and managed risk situation before an event occurs. Nuclear forensic exercises are often scenario based or analytical in scope. Through exercises, stakeholders can evaluate their capabilities and determine performance under realistic conditions, while also assessing roles and responsibilities, and information sharing pathways and mechanisms. Exercises provide the opportunity to refine response and recovery plans and coordination between stakeholders. The outcomes and findings from exercises should be used to identify remedial actions, optimize techniques and provide new ideas to improve the overall response. In addition, by sharing the findings with trusted partners, States can enhance their collective capacity to address emerging threats.

EDUCATION AND EXPERTISE DEVELOPMENT

9.8. Education and expertise development are key elements of an effective, sustainable nuclear forensic capability. A State should have access to technical staff possessing expertise spanning the nuclear and geochemical disciplines most relevant to nuclear forensics. To ensure a sufficient nuclear forensics workforce, it will be critical to develop the next generation of scientists by creating an academic pathway from undergraduate to postdoctorate study in areas such as radiochemistry, nuclear engineering and physics, isotope geochemistry, materials science and analytical chemistry. Practical measures may include:

(a) Encouraging collaboration and exchange between the academic, scientific and policy communities within the State to include students, university faculties, technical experts working in the State’s laboratories and government officials;
(b) Providing resources, such as scholarships, fellowships and internships, to students in the fields listed above at undergraduate, graduate and postgraduate levels, including opportunities for practical research in laboratory facilities;
(c) Providing assistance to universities to support the development of educational programmes relevant to nuclear forensics, including the promotion of an interdisciplinary approach (e.g. bringing together chemistry and physics departments to teach a joint nuclear forensics curriculum);
(d) Facilitating the capture and transfer of the unique technical knowledge of current experts through the mentoring of younger nuclear forensic scientists.

RESEARCH AND DEVELOPMENT

9.9. Nuclear forensics is a developing discipline of forensic science. Research and development is essential to build confidence in nuclear forensic findings and evaluate the reliability of nuclear forensic signatures as a basis to determine origin and history. In particular, research should focus on areas such as improving procedures and analytical techniques for the categorization and characterization of nuclear and other radioactive material, identification of nuclear forensic signatures for inclusion in a national nuclear forensics library, understanding how signatures are created, persist and are modified throughout the nuclear fuel cycle, and how the signatures can be accurately measured [28].

9.10. Engaging in research and development that promotes the science of analysing nuclear and other radioactive material can strengthen a national nuclear forensic capability. In addition, peer review through the scientific process promotes acceptance of, and confidence in, techniques for this type of analysis and interpretation. Acceptance by the scientific community allows these tools to be adopted for use during an actual nuclear forensic examination.

REFERENCES

[1] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Establishing the Nuclear Security Infrastructure for a Nuclear Power Programme, IAEA Nuclear Security Series No. 19, IAEA, Vienna (2013).

[3] KRISTO, M.J., SMITH, D.K., NIEMEYER, S., DUDDER, G.B., Model Action Plan for Nuclear Forensics and Nuclear Attribution, Rep. UCRL-TR-202675, Lawrence Livermore Natl Lab., Livermore, CA (2004).

[4] The Convention on the Physical Protection of Nuclear Material, INFCIRC/274/Rev. 1, IAEA, Vienna (1980).

[5] EUROPEAN POLICE OFFICE, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL CIVIL AVIATION ORGANIZATION, INTERNATIONAL CRIMINAL POLICE ORGANIZATION–INTERPOL, UNITED NATIONS INTERREGIONAL CRIME AND JUSTICE RESEARCH INSTITUTE, UNITED NATIONS OFFICE ON DRUGS AND CRIME, WORLD CUSTOMS ORGANIZATION, Nuclear Security Recommendations on Nuclear and Other Radioactive Material out of Regulatory Control, IAEA Nuclear Security Series No. 15, IAEA, Vienna (2011).

[6] EUROPEAN POLICE OFFICE, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL POLICE ORGANIZATION, WORLD CUSTOMS ORGANIZATION, Combating Illicit Trafficking in Nuclear and other Radioactive Material, IAEA Nuclear Security Series No. 6, IAEA, Vienna (2007).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5), IAEA Nuclear Security Series No. 13, IAEA, Vienna (2011).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Identification of Radioactive Sources and Devices, IAEA Nuclear Security Series No. 5, IAEA, Vienna (2007).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL CRIMINAL POLICE ORGANIZATION–INTERPOL, UNITED NATIONS INTERREGIONAL CRIME AND JUSTICE RESEARCH INSTITUTE, Radiological Crime Scene Management, IAEA Nuclear Security Series No. 22-G, IAEA, Vienna (2014).

[10] Treaty on the Non-Proliferation of Nuclear Weapons, INFCIRC/140, IAEA, Vienna (1970).

[11] Amendment to the Convention on the Physical Protection of Nuclear Material, GOV/INF/2005/10-GC(49)INF/6, IAEA, Vienna (2005).

[12] International Convention for the Suppression of Acts of Nuclear Terrorism, A/59/766, United Nations, New York (2005).
[13] International Convention for the Suppression of Terrorist Bombings, A/52/653, United Nations, New York (1997).
[14] International Convention for the Suppression of the Financing of Terrorism, A/RES/54/109, United Nations, New York (1999).
[15] Protocol of 2005 to the Convention for the Suppression of Unlawful Acts against the Safety of Maritime Navigation, International Maritime Organization, London (2005).
[16] Protocol of 2005 to the Protocol for the Suppression of Unlawful Acts Against the Safety of Fixed Platforms Located on the Continental Shelf, International Maritime Organization, London (2005).
[17] Convention on the Suppression of Unlawful Acts Relating to International Civil Aviation, International Civil Aviation Organization, Beijing (2010).
[18] Protocol Supplementary to the Convention for the Suppression of Unlawful Seizure of Aircraft, International Civil Aviation Organization, Beijing (2010).
[19] United Nations Security Council resolution S/RES/1373 (2001), UN, New York (2001).
[20] United Nations Security Council resolution S/RES1540 (2004), UN, New York (2004).
[21] PARKINSON, A., COLELLA, M., EVANS, T., The development and evaluation of radiological decontamination procedures for documents, document inks, and latent fingermarks on porous surfaces, J. Forensic Sci. **55** (2010) 728–734.
[22] COLELLA, M., PARKINSON, A., EVANS, T., LENNARD, C., ROUX C., The recovery of latent fingermarks from evidence exposed to ionizing radiation, J. Forensic Sci. **54** (2009) 583–590.
[23] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Quality Management Systems: Requirements, ISO 9001:2008, ISO, Geneva (2008).
[24] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Environmental Management Systems: Requirements with Guidance for Use, ISO 14001:2004, ISO, Geneva (2004).
[25] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2005, ISO, Geneva (2005).
[26] BRITISH STANDARDS INSTITUTION, Occupational Health and Safety Management Systems: Requirements, OHSAS 18001:2007, BSI, London (2007).
[27] HILL, D., "Emerging themes from the Global Initiative to Combat Nuclear Terrorism Nuclear Forensics Working Group", Nuclear Security: Enhancing Global Efforts (Proc. Int. Conf. Vienna, 2013), IAEA, Vienna (2014).
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Nuclear Forensics in Combating Illicit Trafficking of Nuclear and Other Radioactive Material, IAEA-TECDOC-1730, IAEA, Vienna (2014).
[29] GARRETT, B., MAYER K., THOMPSON, P., BÍRÓ, T., LASOU, G., "The Nuclear Forensics International Technical Working Group (ITWG): An Overview", Nuclear Security: Enhancing Global Efforts (Proc. Int. Conf. Vienna, 2013), IAEA, Vienna (2014).

[30] PREPARATORY COMMISSION FOR THE COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL CIVIL AVIATION ORGANIZATION, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, INTERPOL, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, WORLD METEOROLOGICAL ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSR Part 7, IAEA, Vienna (2015).

[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Radioactive Waste, IAEA Safety Standards Series No. GSR Part 5, IAEA, Vienna (2009).

Annex I

FORENSIC SCIENCE DISCIPLINES

I–1. This annex provides descriptions of some of the major forensic science disciplines, with a focus on disciplines deemed likely to yield information useful to the needs of an investigation of a nuclear security event.

I–2. The majority of these disciplines have considerable history within the forensic sciences; hence, they are referred to as ‘traditional forensic disciplines’. The investigative value of binary form data (‘digital evidence’) has been recognized for decades, but the growth in the numbers and types of device that capture digital evidence has increased its importance for investigative purposes. Owing to the fact that the tools and techniques for analysing digital evidence and for interpreting results continue to evolve and are important to the forensic examination, they are considered in a later section on an emerging forensic science discipline.

TRADITIONAL FORENSIC SCIENCE DISCIPLINES

Analysis of biological evidence

I–3. Specimens of biological origin that might be recovered as evidence at the scene or from a person, place or thing of interest to an investigation of a nuclear security event include blood, semen and saliva. Human biological evidence containing nuclear DNA (nDNA) can be of particular value because it is possible to associate the test results with one individual with a degree of reliability that is acceptable for criminal justice purposes (i.e. test results are capable of individualization).

I–4. Mitochondrial DNA (mtDNA) is inherited through the maternal line and would be shared in common among all maternally related individuals (e.g. siblings, mother and maternal grandmother). Consequently, mtDNA results are less useful for purposes of individualization but might assist in narrowing the focus of the investigation. In addition, mtDNA can be recovered from biological specimens where nDNA concentrations are insufficient for any meaningful analysis. These specimens include naturally shed hairs, hair fragments, bones and teeth — any of which might be recovered at the scene of a nuclear security event.

I–5. A second category of specimens of biological origin include materials of animal, plant or fungal origin, such as feathers, plant matter (e.g. leaves, pollen, seeds and stems) and spores. Analysis of such materials might offer clues as to, for example, geographical areas associated with the packaging, storage or transport of nuclear and other radioactive material.

Analysis of patterns and impressions

I–6. The analysis of the patterns found in fingerprints (i.e. finger marks), palm prints and sole prints is known as friction ridge analysis. This technique has been used for more than a century to identify individuals. Friction ridge analysis and nDNA analysis are the primary forensic disciplines from which results can be considered to enable individualization. Use of friction ridge analysis might yield similar results to those of nDNA analysis, and should be considered in developing the forensic examination plan, especially if fingerprints, palm prints or sole prints can be recovered from the scene of the event itself or from the nuclear or other radioactive material, or the container used to store or transport the material. Various databases of fingerprints and palm prints are available as an aid in associating these patterns with an individual and are accessible to law enforcement, such as through requests made to INTERPOL. In a forensic context, a database is a searchable collection of data or information, usually but not necessarily, in an electronic or digital format. The Integrated Automated Fingerprint Identification System, in the United States of America, is one such example.[1]

I–7. In addition to fingerprints, palm prints and sole prints, other patterns might be found at a crime scene or at other scenes associated with the investigation. These patterns are often referred to as impression evidence and occur when an object such as a shoe or tyre leaves an imprint on a surface. Other patterns that might be analysed include markings on bullets and on cartridge cases, ear prints, lip prints, some bloodstains, bite marks and glove prints. Unlike friction ridge analysis, however, analysis of these other patterns is unlikely to allow individualization. Instead, the results may enable the pattern to be associated with a class of people or objects — for example, a brand and size of shoe or tyre. Such results can be important to narrowing the focus of any investigation of a nuclear security event.

[1] See https://www.fbi.gov/about-us/cjis/fingerprints_biometrics/iafis/iafis.

Analysis of tool marks and firearms

I–8. Analysis of tool marks and firearms exploits the markings generated when a hard object, such as a tool or the firing pin of a firearm, comes into contact with a relatively soft object. Comparisons of tool marks and markings from firearms can be considered a specialized form of impression analysis. Analysis of marks left by a tool or firing pin can be used to narrow the focus of an investigation, both by indicating certain manufacturers or manufacturing processes of tools or firearms and by eliminating others. These marks might be found on the nuclear or radioactive material itself, on the container used to store or transport the material, or on other objects recovered from the crime scene or other scenes of interest to the investigation.

Analysis of hair

I–9. Humans and animals routinely shed hair. These hairs might be left at a crime scene or might be transferred to another individual at the scene or at another location of interest for investigative purposes. Therefore, an investigation of a nuclear security event should consider the possibility that hair might have been shed onto, or in the vicinity of, the nuclear and other radioactive material out of regulatory control. Microscopic analysis of hair is useful with regard to class characteristics, rather than individual characteristics. That is, results can associate the hair with a type of person (based, e.g., on hair colour or use of dye) rather than on a unique individual. Such results can be useful when excluding certain persons from the pool of possible sources of the hair, thus narrowing the focus of the investigation.

Analysis of fibres

I–10. Analysis of fibres by microscopic examination has a long history of use in forensic science. Fibres can include synthetic materials, such as acrylic, nylon and polyester, as well as botanical fibres, such as those used in many ropes and twines. Such examinations are similar to those conducted on hairs and carry similar limitations — namely that class characteristics can be identified but that individualization is impossible. More recently, modern methods of instrumental analysis, such as Fourier transform infrared spectroscopy, have been used on fibres. Instrumental methods yield additional information of potential value to an investigation. Overall, results from the analysis of fibres may confirm that fibre transfer occurred when one object came into contact with another object, thus substantiating an association of people, places or things with nuclear and other radioactive material out of regulatory control.

Examination of questioned documents

I–11. The examination of questioned documents involves comparison and analysis of documents and of the printing and writing instruments associated with them. The goals of such examinations include:

- Identifying or eliminating individuals as the source of the handwriting;
- Determining whether a document is the output of mechanical or electronic imaging devices, such as printers, copying machines and fax equipment;
- Identifying or eliminating particular machines as the source of printing or typewriting;
- Revealing alterations, additions or deletions;
- Deciphering and restoring damaged, deleted or obscured parts of a document;
- Estimating the age of the document;
- Recognizing and preserving other physical evidence that might be present on the document, such as fingerprints, hairs, fibres and other biological material.

I–12. Such examinations should, therefore, be considered when developing the forensic examination plan whenever documents are recovered in association with nuclear and other radioactive material out of regulatory control.

Analysis of paints, coatings and other surface materials

I–13. Analysis of paints, coatings and other polymeric materials can be valuable to the investigation of a nuclear security event, especially in situations where containers are recovered in connection with nuclear or other radioactive material. Such containers might have writing or other markings on them or within. Similarly, the containers might have polymeric materials used, for example, to cushion the material or as a seal. Analysis of the components of any paints, coatings and other polymeric materials might yield results that aid in identifying regions of the world from which they originated.

Analysis of explosives

I–14. Analysis of explosives is performed on a range of materials. For a configured explosive device that failed to detonate, both the explosive and other components of the device are of evidentiary value. In the event that a device did detonate, evidence of interest includes: unburned or unconsumed powders, liquids or slurries; fragments of the device, including undetonated or unburned explosives; and objects in the immediate vicinity of an explosion that may contain residue from the explosive or fragments of the device. Interpretation of analytical results might suggest a particular group or individual, based on the design, the materials of construction and records of purchase of these materials. Consequently, all forensic examination plans will be influenced by the presence of any explosives at the crime scene.

Forensic medicine

I–15. Through its two main branches, clinical forensic medicine and forensic pathology, forensic doctors could provide expertise in cases related to nuclear forensics.

I–16. Clinical forensic medicine involves the clinical examination of living subjects in cases of injuries, burns, explosives and complications occurring related to the effects and consequences of a nuclear security event. Clinical forensic expertise is concerned with the type and nature of the injuries (or burns), whether or not they are caused by exposure to nuclear or other radioactive material, the date of the injuries, the period of treatment and resultant complications, and whether there is any disability (temporary or permanent).

I–17. Forensic pathology involves the application of medical knowledge to the examination of human remains. The primary tool used for this purpose is an autopsy. Typical goals of forensic pathology include determining the cause and manner of death, identifying the nature and extent of injuries, and establishing the identity of the remains.

I–18. Many laboratory methods can be used to aid forensic medicine, including those methods associated with nDNA and mtDNA examinations (see para. I–4), methods of examining humans (e.g. X ray imaging, magnetic resonance imaging and computer axial tomography) and modern instrumental methods of analysis (e.g. gas chromatography–mass spectrometry, liquid chromatography and inductively coupled plasma mass spectrometry).

I–19. In the case of a victim of a nuclear security event, forensic pathology can be useful for determining whether a victim succumbed to the effects of exposure to radiation or to some other cause. For a nuclear security event in which there is dispersal of nuclear or other radioactive material, the findings of examinations conducted by forensic pathologists might prove useful in estimating the distance of each victim from the dispersal point.

Analysis of digital evidence

I–20. The importance of the analysis of digital evidence — most often of binary form data — has grown with the expansion in both the types of device that record such data and the numbers of such devices in use by individuals, businesses and government institutions. Forensic methods may be used to locate data contained on media and within the operating system or applications. Potential sources of digital evidence include, but are not limited to:

- Desktop, laptop and tablet computers, as well as hard disk drives, memory cards and universal serial bus (USB) flash drives;
- Mobile phones;
- Security and surveillance cameras, such as those used by banks at automated teller machines and by many businesses and some residential buildings or communities;
- Traffic cameras, used to spot traffic infractions or to monitor traffic flow;
- Portable media players;
- Digital cameras.

Digital instrumentation and control systems within a facility may also yield digital evidence. In the context of an investigation of a nuclear security event, such devices, or the evidence from them, might be recovered at or near the scene where nuclear or other radioactive material is seized, along routes that the material might have travelled, and from individuals suspected of association with events culminating in the seizure of the material. The prevalence of digital recording devices might enable the movement of nuclear and other radioactive material to be mapped chronologically and geographically.

Annex II

TECHNIQUES FOR CHARACTERIZATION

COMMONLY USED TECHNIQUES IN NUCLEAR FORENSIC ANALYSIS

II–1. This annex is based on chapter 21 of Ref. [II–1] and describes some of the most commonly used techniques in nuclear forensic analysis, as presented in Table 3, in Section 5. This list of techniques is representative and not exhaustive. To complement this information, outcomes of a coordinated research project on the application of nuclear forensics in illicit trafficking of nuclear and other radioactive material are reported in Ref. [II–2].

Physical characterization, including visual inspection and photography

II–2. Visual inspection of a sample may provide information related to its identity, especially if serial numbers or other identifying marks are present. Alternatively, the size and shape can be sufficient to identify some items. A combination of dimensional measurements and weight of the sample can be used to calculate the density. For some chemical compounds, the colour of the material can be an important indicator. The use of a calibrated length and colour scale facilitates the documentation of these physical measurements.

Optical microscopy

II–3. Optical microscopy is the first method to inspect the sample using magnification. An optical microscope uses magnifying light optics and reflected or transmitted methods of sample illumination to present magnified images of the sample to the user's eyes. Viewing samples under transmitted polarized light can also reveal information on sample composition and homogeneity. Light microscopes can readily magnify an image up to 1000x.

Scanning electron microscopy and X ray spectrometry

II–4. Scanning electron microscopy (SEM) provides image magnifications up to 10 000x with a conventional thermal filament source, or 500 000x with a field emission source. In SEM, a finely focused electron beam scans the sample. The interaction of the energetic incident electron beam and the sample produces backscattered electrons, secondary electrons and X rays. By measuring the signal produced as a function of scan position, an image, or map of the sample, can be displayed. Each type of signal conveys different information about the sample. For example, secondary electrons convey high resolution information about sample morphology. A map of the relative intensity of backscattered electrons will show the spatial distribution of material composition based upon the average atomic number of the imaged sample.

II–5. The X rays generated during SEM or electron microprobe analysis are a way of measuring the elemental composition of samples. The X rays can be analysed quantitatively by either of two methods. First, an energy dispersive X ray spectrometer (EDX) uses a solid state detector to simultaneously measure the energy and rate of incident X rays. Second, in an electron microprobe configuration, a wavelength dispersive X ray spectrometer (WDX) uses an analysing crystal to sequentially diffract selected X rays into a gas proportional counter. X ray analysis is limited to a spatial resolution of around 1 μm. The detection limit of X ray analysis is approximately 0.1%, which is element dependent. SEM coupled with EDX or WDX can be used to map the abundance and spatial distribution of the elements in the sample.

X ray fluorescence analysis

II–6. X ray fluorescence (XRF) analysis is useful for non-destructive elemental quantification of a wide variety of samples. An incident X ray beam excites characteristic secondary X rays in a solid sample, which are counted on a solid state or proportional counter. The detection limits for XRF are in the range of 10 parts per million (ppm). Despite the low X ray energies emitted, the analysis of light elements (e.g. boron, carbon and oxygen) is possible using mass absorption corrections and an analysing crystal.

X ray diffraction analysis

II–7. X ray diffraction (XRD) analysis is a method for identifying the chemical structure of crystalline material. An X ray beam that impinges on ordered crystalline lattices undergoes constructive and destructive interference, which depends on the spacing of the lattice, the wavelength of the X rays and the angle of incidence of the X ray beam. By rotating the sample relative to a fixed X ray source, variations in interference occur, leading to characteristic diffraction patterns. These diffraction patterns can be compared with reference spectra to identify the specific crystalline phase. XRD cannot generate diffraction patterns from amorphous (non-crystalline) material.

Fourier transform infrared spectroscopy

II–8. Fourier transform infrared spectroscopy is useful for the identification of chemical compounds. The sample is exposed to a broad band of infrared frequencies, and the intensity of the reflected or transmitted infrared radiation is measured as a function of frequency. From this, an infrared absorbance spectrum is constructed. Absorption at specific frequencies is characteristic of certain bonds. Thus, the infrared spectrum identifies the various bonds and functional groups within the molecule. There are also compilations of infrared spectra that help to identify unknown compounds or, at least, to place them into certain molecular classes.

Radioactive counting techniques

II–9. Each radioactive isotope emits radiation of known types and energies at a known rate determined by its activity. By measuring the radiation emitted by the sample, it is possible to quantify the amount of each isotope measured present. There are four types of radiation that could be considered for measurement: alpha, beta, gamma and neutron. Each type of radiation has its own properties and methods of detection. The two most important for nuclear forensics are gamma and alpha spectrometry, and they are further described in paras II–10 to II–13.

II–10. Gamma spectrometry is the first technique that is used when seized nuclear or other radioactive material is initially categorized as part of a nuclear forensic examination, owing to the ease of making measurements and the fact that it is a non-destructive technique and does not require sample preparation. Gamma rays (i.e. photons with energies in the range of 10 keV to more than 500 keV) are measured, although they are attenuated by packing or shielding material, especially lead. The initial categorization measurements at the scene are carried out with portable gamma spectrometers, for example sodium iodide hand-held identifiers or portable high purity germanium detectors. In laboratories, more sophisticated gamma spectrometry systems with greater sensitivity and resolution are used. Thus, gamma rays with smaller abundances can be measured with higher resolution. Energies close to each other can be resolved in the spectrum. Commercially available software is used to resolve the low energy spectra observed for plutonium and uranium, and allows calculation of the isotopic composition of the material. It should, however, be noted that some nuclides, such as ^{242}Pu or ^{236}U, cannot be detected by gamma spectrometry; instead, mass spectrometry is used.

II–11. Gamma spectrometry also plays a key role in neutron activation analysis, where it is used to measure those nuclides created by the activation of samples in a reactor or neutron generator.

II–12. Alpha spectrometry detects alpha particles, which are He^{2+} ions with energies in the range of 3–8 MeV. Alpha spectrometry is a destructive technique. Alpha particles are easily stopped because of their strong interaction with matter and, hence, radiochemical preparation of samples for counting by alpha spectrometry is required.

II–13. Radiochemistry followed by alpha spectrometry is important for measuring ^{238}Pu and $^{239+240}$Pu activity. The radiochemical separation of plutonium and americium is especially important because the alpha particles emitted by ^{241}Am and ^{238}Pu have similar energies and, thus, overlap in the spectrum. Similarly, the alpha energies of ^{239}Pu and ^{240}Pu are very close and cannot be resolved in the spectrum. Consequently, they are measured as a sum (i.e. $^{239+240}$Pu). The atomic ratio of ^{240}Pu/^{239}Pu is obtained by the use of mass spectrometry.

Chemical assay

II–14. Chemical titration and controlled potential coulometry are standard methods for the determination of the elemental concentration of neptunium, plutonium, uranium or other major components of nuclear fuel material for accountability measurements or verifications. In chemical titration, the sample is made to react with an exactly measured amount of a selective reagent of known composition, leading to the completion or characteristic end point of a well known stoichiometric reaction. Titration methods are designated, inter alia, according to the mode of detection of the end point (e.g. potentiometric and spectrophotometric titrations). Using controlled potential coulometry, the element to be analysed is selectively oxidized or reduced at a metallic electrode maintained at a selected potential. The number of electrons lost through oxidation or gained through reduction is a measure of the amount of element present in the sample.

II–15. The precision and accuracy of these methods is better than 0.1% using a typical sample size of a few hundred milligrams. The methods are well established and are used routinely in nuclear accountancy and safeguards laboratories. They can, therefore, be very effective for the characterization of nuclear material, provided that samples are at least a few tenths of a gram.

Radiochemistry

II–16. Many samples are too complex for all of the radioactive isotopes present to be measured without initial separation and purification. By utilizing the differences in chemical properties of the elements, it is possible to devise schemes to separate elements, or groups of elements, to allow the measurement of the isotopes present by radioactive counting methods or mass spectrometry. The isotopes measured relate quantitatively to the original sample by referencing to an internal isotopic standard called a ‘spike’. The chemical separation and purification steps increase both the sensitivity and selectivity of the technique. Radiochemistry is especially important to allow the measurement of isotopes that are present at low activity and are best measured by their alpha emissions or by mass spectrometry. Radiochemistry, in combination with radioactive counting techniques and mass spectrometry, has the potential to measure down to femtogram (10^{-15} g) levels for some isotopes.

Radiography

II–17. Radiography techniques may be beneficial for determining the spatial distribution and activities of radionuclides in a sample. For example, fission track analysis and alpha track analysis can locate and quantify actinides within a sample using solid state nuclear track detectors, and methods using photographic films or modern charged couple device based technologies can locate and identify alpha and beta emitters.

Mass spectrometry

II–18. Mass spectrometry is used to determine the isotopic composition of elements in a given material. Mass spectrometry can also provide quantification (often called an ‘assay’ when applied to major constituents of the sample) of these elements by adding a known quantity of a specific isotope. This is known as isotope dilution mass spectrometry (IDMS). Mass spectrometric methods are able to analyse both radioactive and stable isotopes. In mass spectrometry, atoms and molecules are converted into positively or negatively charged ions. The ions are then separated according to their mass to charge ratio, and the intensities of the resulting mass-separated ion beams are measured. Elemental mass spectrometric techniques generally have high selectivity due to the mass analysis step, except in specific cases of isobaric interferences. Mass spectrometry offers extremely high precision and accuracy of analysis as well as high abundance sensitivity.

Thermal ionization mass spectrometry

II–19. In thermal ionization mass spectrometry (TIMS), a sample is deposited on a metal filament, which is heated by the passage of an electrical current maintained in a high vacuum. If the ionization potential of a given element is low enough, compared to the work function of the filament, then a fraction of the atoms of that element are ionized via interaction with the filament surface at high temperature. The masses are then resolved in a mass spectrometer in a high vacuum using a magnetic sector. The specificity of the TIMS analysis reflects both the chemical separation steps and the ionization temperature. TIMS is capable of routinely measuring isotopic ratios on nanogram (10^{-9} g) or picogram (10^{-12} g) samples or, for rare samples, down to tens of femtograms (10^{-15} g) using special pre-concentration techniques. TIMS routinely measures differences in isotope mass ratios on the order of 1 ppm.

Inductively coupled plasma mass spectrometry

II–20. Analysis by inductively coupled plasma mass spectrometry (ICP-MS) requires the sample to be aspirated as a solution into an inductively coupled plasma, where the high temperature of the plasma breaks the sample down into its constituent atoms and ionizes these species. In addition to measuring isotope ratios, ICP-MS is useful both as a sensitive elemental survey tool and as a method for precisely quantifying trace elemental constituents of a sample. The detection limits range from 0.1 parts per billion (ppb) to approximately 10 ppb in solution. ICP-MS is problematic for measuring some elements with lower atomic numbers, due to background interferences or poor ionization efficiency (e.g. carbon, oxygen, phosphorous, potassium, silicon and sulphur).

Secondary ion mass spectrometry

II–21. Secondary ion mass spectrometry (SIMS) is used for both elemental and isotopic analysis of samples, including small particles. SIMS uses a finely focused primary ion beam (e.g. Cs^+, Ga^+ or O_2^+ to sputter the sample surface). The sputtering process produces secondary ions (characteristic of the sample) that can be analysed by a mass spectrometer. In the ‘microscope’ mode, a relatively large primary ion beam bombards the sample, and the spatial position of the resulting secondary ions is maintained and magnified throughout the mass spectrometer. A position sensitive imaging detector displays and records the isotopic image. In the ‘microbeam’ mode, a finely focused primary ion beam scans the sample in a manner similar to an electron microscope. The resulting secondary ion signal is then measured and correlated with the position of the primary ion beam to generate the isotope image. Ablation by the focused ion beam of the sample surface yields a depth profile that is extremely valuable for documenting compositional gradients or surface alteration.

Gas chromatography–mass spectrometry

II–22. Gas chromatography–mass spectrometry (GC–MS) is a technique useful for detecting and measuring trace organic constituents (i.e. ppm) in a bulk sample. In GC–MS, the volatile components of a sample are separated in the gas chromatograph and identified in the mass spectrometer. The mass spectrometer ionizes and fragments each component as it elutes from the chromatography column. Many different ionization methods can be used, but the most common for GC–MS is electron impact. The mass spectrometer measures the intensity of ions of various masses, by either simultaneous or sequential detection, depending on the type of mass spectrometer. The resulting plot of relative intensity versus mass to charge ratio is a ‘mass spectrum’. There are extensive libraries of mass spectra that help to identify unknown compounds detected by using GC–MS.

Transmission electron microscopy

II–23. In transmission electron microscopy (TEM), an energetic electron beam is transmitted through an ultra-thin sample (approximately 100 nm thick). TEM is capable of greater magnifications than SEM and is able to image extremely fine sample structure. Transmitted electrons can undergo diffraction effects, which can be used like XRD to identify crystal phases in the material.

REFERENCE

[II–1] KRISTO, M.J., “Nuclear forensics”, Handbook of Radioactivity Analysis, 3rd edn (L’ANNUNZIATA, M.F., Ed.), Elsevier, Oxford (2012).

[II–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Nuclear Forensics in Combating Illicit Trafficking of Nuclear and Other Radioactive Material, IAEA-TECDOC-1730, IAEA, Vienna (2014).

Annex III

EXAMPLES OF EDUCATION, TRAINING, EXERCISES, AND RESEARCH AND DEVELOPMENT ACTIVITIES

III–1. This annex describes some of the capacity building activities being implemented internationally.

EDUCATION

III–2. In 2010, the IAEA established the International Nuclear Security Education Network (INSEN) to ensure effective nuclear security practices by developing, sharing and promoting educational excellence. INSEN includes educational and research institutes involved in, or planning to be involved in, nuclear security education. Members of INSEN collaborate on the development of textbooks, teaching tools and instructional material, continuing education of faculty instructors, student exchange to foster information sharing, research and development to promote technical confidence, evaluation of academic theses and dissertations, and performance metrics on the effectiveness of nuclear security education.

TRAINING

III–3. The IAEA has designed a series of training courses to satisfy the requirements of different audiences covering various facets of nuclear forensics in support of an investigation of a nuclear security event. These include: Introduction to Nuclear Forensics, Nuclear Forensics Methodologies, and an affiliated course, Radiological Crime Scene Management. More information is available from the IAEA Nuclear Security Training Catalogue, accessible on the IAEA Division of Nuclear Security web site[1].

III–4. INTERPOL also provides training to interagency multinational groups of law enforcement and scientific personnel on best practices in radiological crime scene management.

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[1] See http://www-ns.iaea.org.

III–5. In addition, training courses are being provided nationally and internationally by Member States.

EXERCISES

III–6. The Nuclear Forensics International Technical Working Group (ITWG) conducts a number of analytical and scenario based exercises, providing an opportunity for laboratories to assess their performance on analysis as well as demonstrate capabilities. The ITWG exercise task group has been crucial in planning, implementing and reporting on collaborative material exercises — also referred to as 'round robins', during which all participating laboratories receive identical samples of nuclear or other radioactive materials as well as, in some cases, non-nuclear evidence and are tasked to perform analyses. The participants conduct analyses and report findings on a 24 hour, 1 week and 2 month schedule. Involvement in the round robins is completely voluntary and open to laboratories that self-declare their measurement capabilities. The results are coded so that the results from each laboratory are reported anonymously and are known only to the exercise coordinator. The outcomes of the exercises demonstrate individual laboratory performance relative to declared analytical capability while also identifying the utility of different analytical methods applied to a common sample. Round robins involve international laboratories and varied materials. Three ITWG collaborative material exercises have been completed:

(a) The 1998–2000 exercise involved six laboratories analysing plutonium oxide.
(b) The 2000–2002 exercise involved ten laboratories analysing high enriched uranium oxide.
(c) The 2010 exercise involved nine laboratories analysing high enriched uranium metal.

III–7. The Global Initiative to Combat Nuclear Terrorism (GICNT) Implementation and Assessment Group conducts tabletop exercises and seminars. The aim of the exercises are:

(a) To develop and foster a common understanding of nuclear forensic capabilities and principles;
(b) To emphasize the importance of nuclear forensics to policy makers and decision makers;
(c) To discuss the relationships of the various communities (including law enforcement, judicial, policy and technical) involved in nuclear forensics;

(d) To explore the policy aspects of sharing information to advance the investigation of nuclear security events;
(e) To identify potential cooperative information sharing partnerships, both nationally and internationally.

RESEARCH AND DEVELOPMENT

III–8. In order to build confidence in nuclear forensics, to further the study of nuclear forensic signatures, to facilitate the development of national nuclear forensics libraries and to promote international collaboration, the IAEA initiated the following coordinated research projects (CRPs):

(a) 2008–2011: Application of Nuclear Forensics in Combating Illicit Trafficking of Nuclear and Other Radioactive Material [III–1].
(b) 2013–present: Identification of High Confidence Nuclear Forensic Signatures for the Development of National Nuclear Forensics Libraries.

III–9. More information is available on all IAEA CRPs on the IAEA web site[2].

REFERENCES

[III–1] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Nuclear Forensics in Combating Illicit Trafficking of Nuclear and Other Radioactive Material, IAEA-TECDOC-1730, IAEA, Vienna (2014).

[2] See http://www-crp.iaea.org.

GLOSSARY

bulk analysis. The analysis of either an entire sample or a portion of the sample to determine the average properties of the measured portion.

chain of custody. The procedures and documents that account for the integrity of physical evidence by tracking its handling and storage from its point of collection to its final disposition. Other terms for this process are ‘chain of evidence’, ‘chain of physical custody’ and ‘chain of possession’.

characterization. Determination of the nature of the radioactive material and associated evidence.

class characteristic. An attribute or feature shared by all members of a class of people or items.

competent authority. A governmental organization or institution that has been designated by a State to carry out one or more nuclear security functions. For example, competent authorities may include regulatory bodies, law enforcement, customs and border control, intelligence and security agencies, health agencies, etc.

designated nuclear forensic laboratory. A laboratory that has been identified by a State as being capable of accepting or analysing samples of nuclear and/or other radioactive material for the purpose of supporting nuclear forensic examinations.

examination. A procedure used to obtain information from evidence in order to reach conclusions concerning the nature of and/or associations related to evidence.

individualization. The ability to associate a forensic result or a set of results uniquely with a single source, such as a person, place or production process.

national nuclear forensics library. An administratively organized collection of information on nuclear and other radioactive material produced, used or stored within a State.

nuclear forensic interpretation. The process of correlating sample characteristics with existing information on types of material, origins, and methods of production of nuclear or other radioactive material, or with previous cases involving similar material.

nuclear forensic science or nuclear forensics. A discipline of forensic science involving the examination of nuclear and other radioactive material, or of other evidence that is contaminated with radionuclides, in the context of legal proceedings.

radiochronometry. The use of measurements of radioactive decay products in a sample of material to determine the time elapsed since the last separation of progeny from the parent material (and thus the 'age' of the material in the measured sample).

radiological crime scene. A crime scene at which a criminal act or other intentional unauthorized act involving nuclear or other radioactive material has taken place or is suspected.

signature. A characteristic or a set of characteristics of a given sample that enables that sample to be compared with reference materials.

trace element. An element in a sample that has an average concentration of less than 1000 μg/g or 0.1% of the matrix composition.

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