Overview of Nuclear Forensics in Support of Investigations

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Abstract. In recognition that nuclear forensics is a key component of nuclear security, the IAEA published in 2006, "Nuclear Forensics Support" (Nuclear Security Series No. 2), which was based on a "Model Action Plan for Nuclear Forensics and Nuclear Attribution," developed by the Nuclear Forensics International Technical Working Group (ITWG). The Model Action Plan outlined a generalized approach for the conduct of a nuclear forensic examination. Since 2006, there have been further advances in nuclear forensics. Nuclear forensic examinations have been successfully applied to cases involving illicit trafficking of highly enriched uranium and plutonium, as well as other events involving nuclear or other radioactive material out of regulatory control. As a result, the IAEA is revising the 2006 document as "Nuclear Forensics in Support of Investigations," which describes the role of nuclear forensics in support of investigations of a nuclear security event and provides context for nuclear forensics within a national nuclear security infrastructure. Additionally, the 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.

1. Introduction

In recognition that nuclear forensics is a key component of nuclear security, the IAEA published in 2006, "Nuclear Forensics Support" (Nuclear Security Series No. 2) [1] as Technical Guidance. Acknowledging that there have been further advances in nuclear forensics since 2006, the IAEA is revising the 2006 document with the new title "Nuclear Forensics in Support of Investigations" as draft Implementing Guidance for publication within the IAEA Nuclear Security Series. The objective of this revised 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 nuclear security events involving nuclear or other radioactive material out of regulatory control. Also included are 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 international cooperation and assistance in nuclear forensics. The essential elements of nuclear forensic capacity building including awareness, education, expertise development and training are 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 or other radioactive materials out of regulatory control.

The revised publication does not provide detailed guidance on the design, equipping or staffing of a laboratory where nuclear forensic examinations may be conducted; nor does it 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.

2. Role of Nuclear Forensics

Despite the existence of national nuclear security infrastructures, there continue to be cases of 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 to as nuclear security events. A nuclear forensic examination may be an important component of the response to a nuclear security event.

2.1 A Model Action Plan

The nuclear forensics model action plan [2] shown in Figure 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.

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.

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, 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.

2.2 National Framework

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 into a nuclear security event, the nuclear forensics model action plan (Figure 1) should be incorporated into the national response plan to the extent possible.

States should ensure that 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 provision for the safe and secure storage of seized nuclear and other radioactive material, as well as 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.

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.

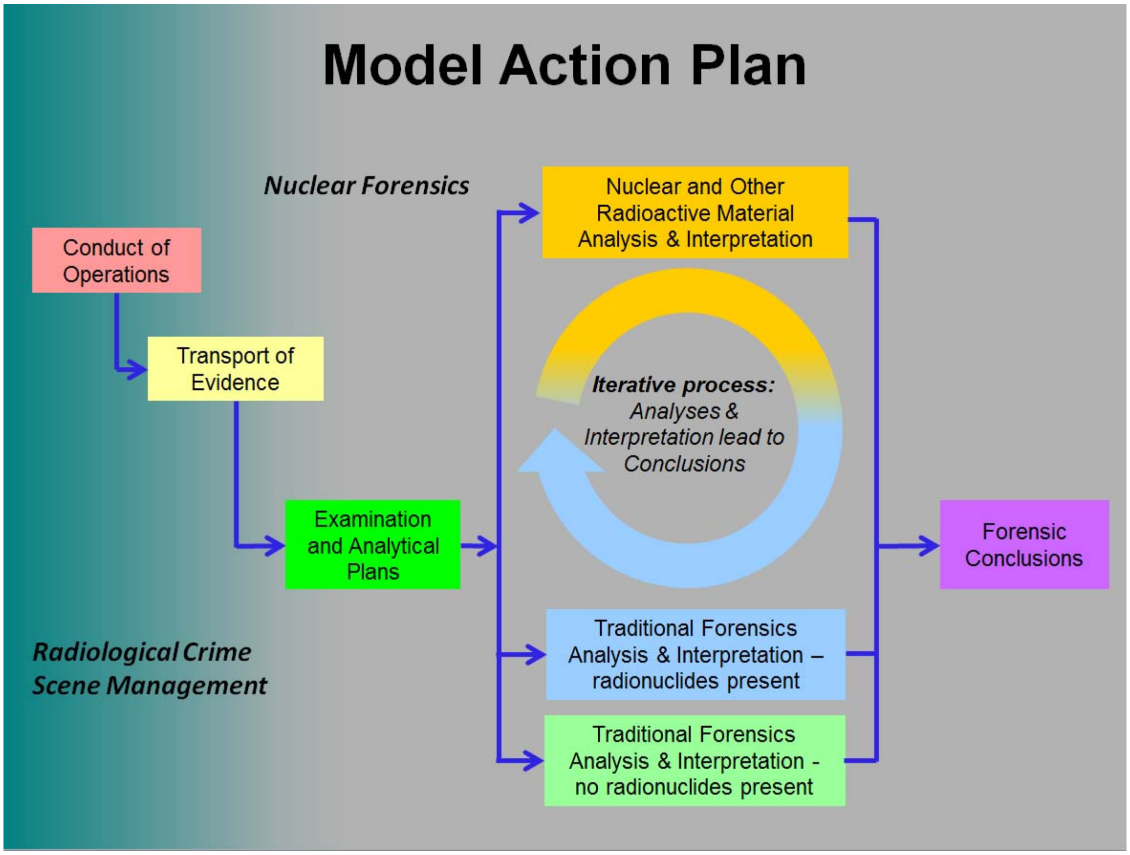

FIG. 1. Illustration of the nuclear forensics model action plan: a process which supports an investigation of a nuclear security event. Background shading indicates the transition from radiological crime scene management to nuclear forensics.

3. Forensics Examination Plan and Corresponding Nuclear Forensics Analytical Plan

For the purposes of investigating a nuclear security event, once the preliminary on-scene assessment has been performed, including categorization[1] 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. The forensic examination plan should describe the requirements of the examinations to be conducted in support of a potential criminal prosecution. Additionally, 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.

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, (for example, DNA analysis or fingerprint examination) over those where the results are likely to identify only a group or class (for example, shoe or tyre impressions, or the presence of a particular type of explosive). However, the presence of other investigative or intelligence information may enhance the

[1] Categorization is performed to identify nuclear security implications and the risk of the seized material to the first responders, law enforcement personnel, and the public.

value of class characteristic results, especially where narrowing the range of possibilities is critical to focusing the investigation.

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.

A nuclear forensic analytical plan should be developed to specifically describe what types of analysis 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[2]. 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.

3.1 Evidence Contaminated with Radionuclides

The conduct of examinations in traditional forensic disciplines and nuclear forensic examinations should complement each other. Both yield results that may 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 association with an individual person, place, thing or event or they allow certain nuclear or other radioactive materials to be excluded from further consideration. The potential for radioactive material to be present as a contaminant on physical evidence presents a particular challenge for examinations conducted in traditional forensic disciplines.

When confronted with the need to conduct examinations in traditional forensic disciplines on evidence contaminated with radionuclides, two approaches are possible. The first approach involves removal of or separation of the radionuclides from the evidence prior to conducting any examinations. This is often referred to as decontamination of the evidence. The second approach involves the conduct of these examinations directly on the evidence contaminated with radionuclides. Both approaches may require input from multiple agencies, in particular from agencies 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 that should be evaluated during the course of the investigation.

The decision whether to attempt 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:

- The nature of the evidence, the contaminant and the examinations to be performed;
- Availability of relevant resources for the conduct of the examinations;
- Information obtained to date through investigative or intelligence methods, and from any related examinations that have been performed;
- National policies and procedures for responding to nuclear security events.

[2] Characterization is performed to determine the nature of the radioactive material and associated evidence.

3.2 Nuclear Forensics Laboratory Analysis

Based on 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, and should follow the nuclear forensic analytical plan.

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 or 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 upon 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 may support precise interpretation.

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

Techniques/methods	**Conducted within**		
	24 hours	**One week**	**Two 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, etc. - Scanning electron microscopy (SEM) - X ray diffraction (XRD)	Nanostructure, morphology, etc. - Transmission electron microscopy
Isotopic analysis	- High resolution gamma ray spectrometry (HRGS)	- Thermal ionization mass spectrometry (TIMS) - Inductively coupled plasma mass spectrometry (ICP-MS)	- Secondary ion mass spectrometry (SIMS) - Radioactive counting techniques
Radiochronometry	- HRGS (for Pu)	- TIMS - ICP-MS	- HRGS (for U) - Alpha spectrometry
Elemental/chemical composition	- X ray fluorescence	- ICP-MS - Chemical assay - Fourier transform infra-red spectrometry - SEM / X ray spectrometry - Isotope dilution mass spectrometry	- Gas chromatography mass spectrometry
Traditional forensic science disciplines	- Collection of evidence associated with traditional forensic disciplines		- Analysis and interpretation of evidence associated with traditional forensic disciplines

The ITWG, an association of nuclear forensic practitioners, has developed a recommendation on the sequencing of techniques to provide the most valuable information as early as possible in the analysis process. This recommendation is based on expert opinion and on experience gathered from three collaborative analytical exercises undertaken by the ITWG. Table I shows the ITWG's recommended sequence of analyses, broken down into techniques that could be performed within 24 hours, one week or two months from the sample's arrival at the designated nuclear forensic laboratory. 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 24 hours, one week, and two months analytical intervals, 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 receipt of a sample(s).

3.3 Nuclear Forensic Interpretation

Once analyses have been performed, it may be necessary to use additional expertise to interpret analytical results and 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, origins and methods of production of nuclear or other radioactive material, or with previous cases involving similar material. Nuclear forensic interpretation provides context, explanations for the analytical results, and the basis of nuclear forensic findings.

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., an 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 is impractical for nuclear forensics to rely on a single sample-to-sample matching. However, combinations of signatures, such as isotopic measurements, impurities and microstructure, when used together, can provide increased confidence in associating a specific sample with a known class of similar material. The use of signature combinations may also enable exclusion — the conclusion that a specific sample is not connected with known classes of materials — which can also be valuable for nuclear forensic interpretation.

Nuclear forensic analysis and interpretation involve a deductive and iterative process, as depicted in Figure 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 may identify likely production processes that could have made the seized material, as well as those processes that could not have made the seized material.

3.4 Nuclear Forensic Findings

Nuclear forensic findings are the products of nuclear forensic analysis and interpretation. These findings may support law enforcement investigations, regulatory inquiries, and policymaking 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, and what were its probable method(s) of production.

In general, confidence in analytical results depends upon three factors: 1) validated methods; 2) certified reference materials; and 3) demonstrated competencies. 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 findings through 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.

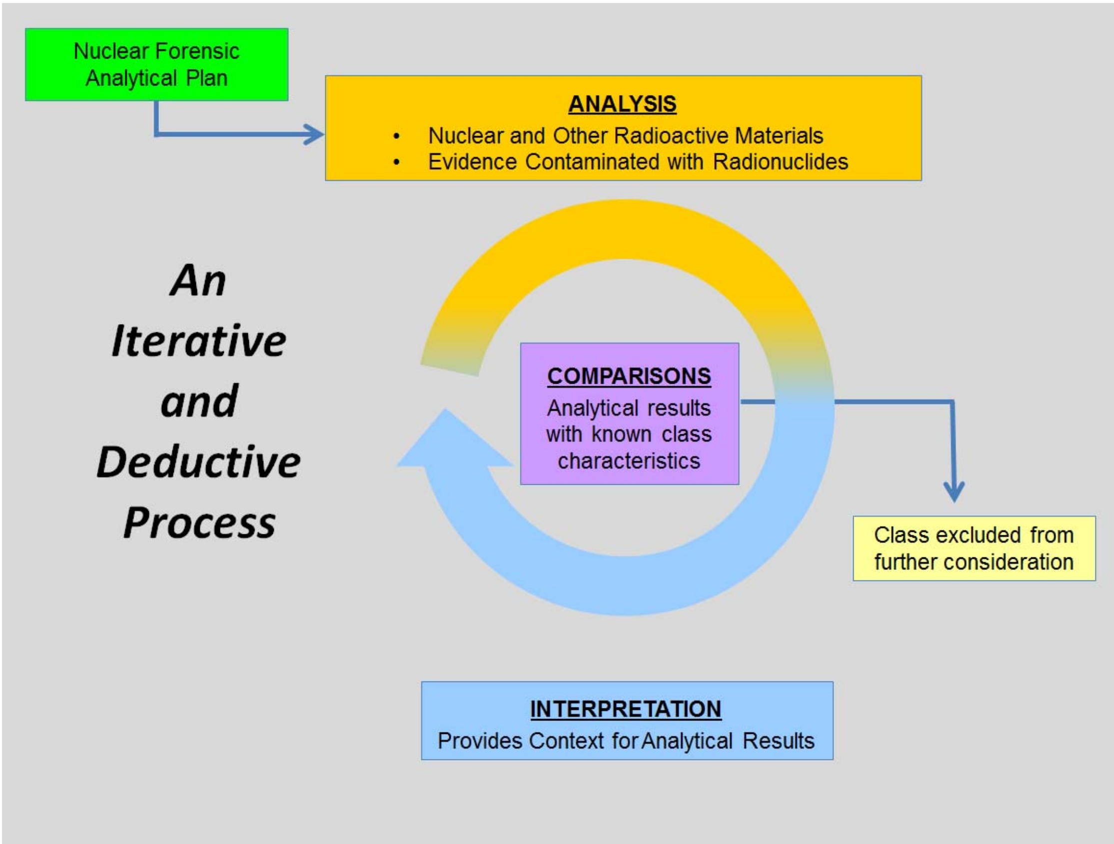

FIGURE 1. Nuclear forensic analysis, comparisons and interpretation: an iterative and deductive process to provide context for analytical results.

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.

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.

Given the general need to strengthen the means of conducting nuclear forensic analysis, States 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.

4. International Cooperation and Assistance

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.

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 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.

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.

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.

5. Nuclear Forensic Capacity Building

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 to an effective nuclear forensic capability. As such, strategies for developing, testing and sustaining nuclear forensic capability and capacity are essential to enabling 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 and effective knowledge management in anticipation of future requirements, and effective education in nuclear science to foster and sustain capabilities.

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 understanding of nuclear forensics among facilitators and developers of a nuclear forensic capability;
- Clarify roles and responsibilities;
- Increase knowledge of nuclear forensics applied to law enforcement investigations and nuclear security vulnerability assessments;
- Encourage the use of common terminology among different organizations and disciplines.

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 into 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 forensics partnerships.

An effective nuclear forensic capability depends upon collaboration between science and technology organizations, law enforcement agencies and other government agencies both nationally and internationally. The development of shared collaboration and cooperation 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 of bolstering this capability.

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 scientific 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 post-doctorate study in areas such as radiochemistry, nuclear engineering and physics, isotope geochemistry, materials science and analytical chemistry.

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 identification and characterization of nuclear and other radioactive materials, identification of nuclear forensic signatures to aid in determinations of material origins and history, understanding how signatures are created, persist and are modified throughout the nuclear fuel cycle, and how the signatures can be accurately measured [3].

Engaging in research and development that promotes the science of nuclear and radioactive material analysis can maintain and improve a national nuclear forensic capability. Additionally, peer review through the scientific process promotes acceptance of and confidence in techniques for nuclear or other radioactive materials analysis and interpretation. Acceptance by the scientific community allows these tools to be adopted for use during an actual nuclear forensic examination.

References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Forensics Support, IAEA Nuclear Security Series No. 2, IAEA, Vienna (2006).

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

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