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Cover Page Footnote

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The Role of Nuclear Forensics for Determining the Origin of Nuclear Materials Out of Regulatory Control and Nuclear Security

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Abstract

The international community recognizes the rise in theft and illicit trafficking of nuclear materials and radioactive sources—for malicious use and nuclear terrorism—as a serious threat. That is why a well-developed nuclear forensics capability is an integral part of a robust nuclear security program and a key element of nuclear security infrastructure. Both pre- and post-detonation nuclear forensics are vital for controlling theft and illicit trafficking of nuclear materials, as well as identifying and tracing their sources. Nuclear forensics analysis and interpretation processes for nuclear security is a systematic process that includes: (1) sample collection and categorization techniques and (2) detailed nuclear forensics analytical plans, which are a laboratory analysis of physical and chemical properties of the collected or seized nuclear and radioactive materials. Besides nuclear materials, the non-nuclear and biological materials present in seized nuclear materials can also provide important information about the source and origin of nuclear materials. Upon complete analysis of the seized materials, the data interpretation to trace the origin of the nuclear and radiological materials is one of the most critical steps to identifying the origin of the materials, which depends on the availability of similar data to compare. So, each country should have its own incident register system (IRS) and collaborate with the International Technical Working Group (ITWG), Incident and Trafficking Database (ITDB), and IAEA for data sharing and interpretation.

Keywords: Illicit trafficking, nuclear security, nuclear forensics, pre- and post-detonation forensics, characterization, interpretation, source tracing

I. Introduction

A. Nuclear Forensics for Nuclear Security

The theft and illicit trafficking of nuclear materials and radioactive sources for malicious use and nuclear terrorism is a high priority concern for nuclear security domestically and internationally **[*1*]**. As per the

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IAEA database, there were more than 2,477 incidents of illicit trafficking of nuclear and radioactive materials between 1993 and 2013. Among them, 16 incidents were related to unauthorized possession of highly enriched uranium (HEU) and plutonium (Pu) **[*2*]**. The increase in illicit nuclear trafficking was recognized as a significant nuclear security threat by the international community. Consequently, they established nuclear forensic science around the mid-1990s for source attribution of interdicted smuggled nuclear materials **[*1, 3*]**. Source attribution determines the origin or potential trafficking routes of the materials and their intended use, which improves nuclear materials' security and physical protection system at a particular location **[*4*]**.

The main goal of a nuclear security regime is to prevent, detect, and respond to nuclear security events such as illicit trafficking of nuclear or radioactive materials and nuclear terrorism. Nuclear forensics is a key technical capability that utilizes signatures inherent to nuclear and radioactive materials to provide information about pre- and post-detonation events (i.e., the spectrum of nuclear security events under investigation). It asks the following questions: How, when, and where were the materials made? What were their intended uses? **[*1, 5, 6*]**. Moreover, nuclear forensics is valid scientific evidence to present before the court of law, which deters illicit nuclear trafficking and nuclear terrorism **[*5*]**. The information obtained from nuclear forensics can respond to nuclear security events and help prevent them **[*3, 6, 7*]**. Thus, the role of nuclear forensics is vital in the fight against illicit trafficking of nuclear and radioactive materials, their malicious use, and global nuclear terrorism **[*3*]**.

A well-developed nuclear forensics capability for a civilian nuclear energy program has been recognized as an important part of a robust nuclear security program and a vital element of a nuclear security infrastructure **[*1, 3, 5*]**. Therefore, one of the major focus areas of the 2016 Nuclear Security Summit (NSS) **[*8*]** was to develop the nuclear forensics capability to trace the origin of the interdicted nuclear materials, identify the smuggling network, and aid in the prosecution of illicit trafficking. Canada has a civilian nuclear energy program and is one of the world's largest suppliers of highly radioactive materials and sealed sources. Hence, Canada decided to enhance its nuclear forensics capability. As per the Canada commitment for a national nuclear forensics capability at the Seoul 2012 NSS, the Canadian National Nuclear Forensics Capability Project (CNNFCP) was started in May 2013 to establish a National Network of Forensics Laboratory (NNFL) and a National Nuclear Forensics Library **[*1, 8*]**. For any country with a civilian nuclear energy program, the nuclear forensics program would be instrumental in identifying unaddressed deficiencies in nuclear materials accounting, control, and physical protection systems **[*6*]**. The main objectives of this brief review paper are to highlight the importance of nuclear forensics for national and global nuclear security and discuss the basic steps in nuclear forensics analysis and interpretation processes to identify the origin of nuclear materials out of regulatory control.

B. Pre-detonation and Post-detonation Nuclear Forensics for Nuclear Security

1. Pre-detonation forensics: Pre-detonation forensics, often called "nonproliferation forensics," focuses on forensics relevant to interdicted nuclear materials. Pre-detonation forensics works using scientific information, law enforcement, and intelligence sources to answer the questions raised by a seized nuclear material; intercepted communication like emails, voice mails, letters, etc.; unusual border activities; and other nuclear-material–related activities. Pre-detonation nuclear forensics tries to answer: Who left that nuclear material and why? Do they have a link to other international nuclear smugglers or terrorist groups? What are the sources of the nuclear material, and when did they get that? How long have those individuals possessed that nuclear material? What was their supply chain? What are their nationality and motives? Also, their biological samples (e.g., blood, DNA, and nails) would provide some clues about the incident **[*7*]**.

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2. Post-detonation nuclear forensics: This nuclear forensics deals with analyzing and tracing nuclear materials after a nuclear detonation or after major nuclear accidents such as Chernobyl and Fukushima. Post-detonation nuclear forensics tries to answer all the pre-detonation events and a few more questions: What type of device is used? Was it uranium or plutonium or something else? How wide is the fallout from the events? What are the health implications, and how do we mitigate them? What was the organization and motive behind the nuclear or radiological attack? If there is any possibility of another attack, what would be the main target? **[*7*]**.

II. Nuclear Forensics Analysis and Interpretation for Nuclear Security

Nuclear forensics analysis is a systematic process and generally follows the same process, as per the flow chart prepared by the IAEA (Figure 1) **[*9*]**. It is a comprehensive process of analyzing nuclear or other radioactive materials, which exploits the chemical and physical properties and the isotopic signatures inherent to nuclear and other radioactive materials to identify the sources, history, and people involved behind the materials and events **[*1*, *9*]**.

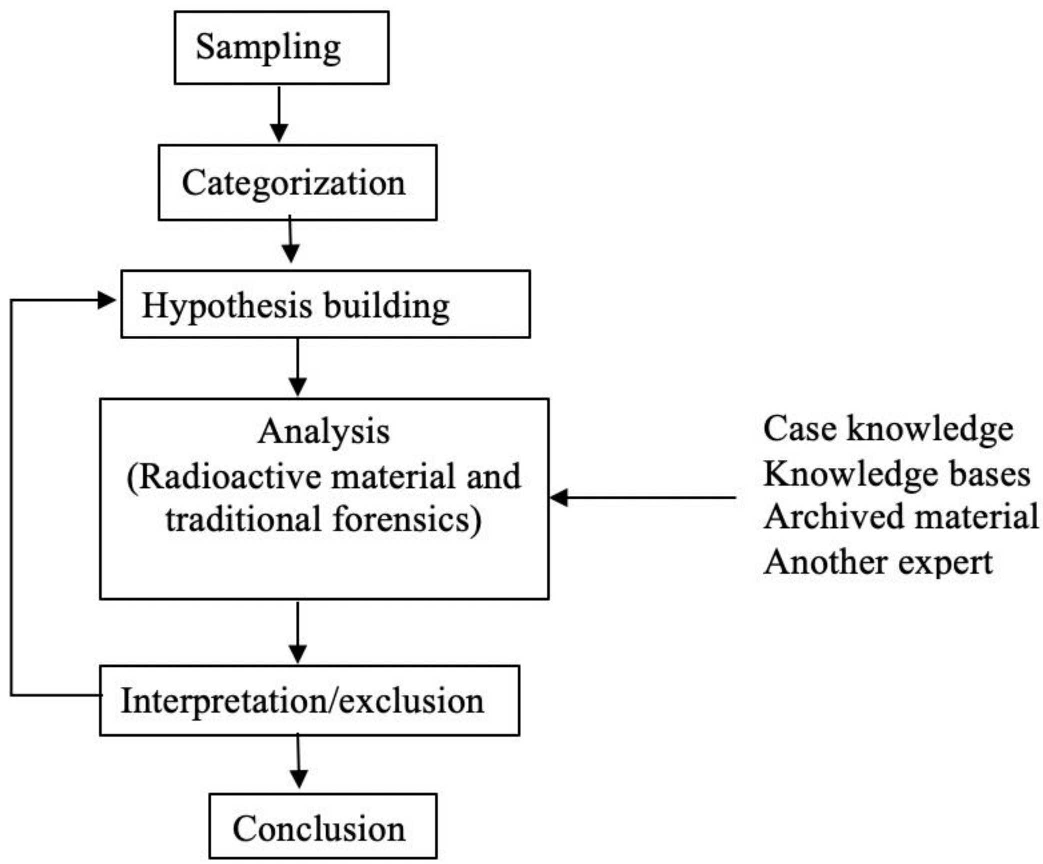

Figure 1. Flow chart of the nuclear forensics analysis process [*9*]

The response to a specific nuclear incident in both pre- and post-detonation events is a graded approach and mainly consists of four different steps: (1) Sample collection, (2) categorization, (3) characterization (i.e., laboratory analyses of the collected samples), and (4) interpretation. A nuclear forensics scientist develops a hypothesis or set of hypotheses based on archive materials or preliminary analyses and then characterizes the samples and tests the hypothesis by comparing with the relevant databases and literature, verifying the presence or absence of signatures. If the signature is absent, a forensic expert either abandons the analysis (i.e., the hypothesis must be rejected) or changes the hypothesis and starts the new analysis process again (Figure 1). However, if the signature is present, additional laboratory analysis may be required to exclude other possible scenarios and determine the origin of the nuclear materials. Thus, nuclear forensics analysis and interpretation are deductive and iterative processes **[*9*]**.

A. Sample Collection and Categorization Techniques

The sample for nuclear forensics may differ from other regular sample collection techniques for scientific analysis. Since nuclear forensics samples and sampling procedures are highly versatile, often diverse and unexpected samples such as gases or aerosols, dust particles, biological materials, large metal pieces, glasses, plastic, and soil are collected from the incident sites **[*3, 6*]**. During sampling, it may be necessary to collect as many samples as possible using a safe handling technique and a proper sample collection protocol **[*3*]**. Nuclear forensic science applies scientific knowledge to legal problems **[*3*]**. If the samples are collected from the illicitly trafficked nuclear material, the chain of custody must be maintained to ensure data quality and reliability for the legal prosecution **[*6, 9*]**. We should remember that sample collection may have legal and practical restrictions and limitations. Immediately after sample collection, the collected or seized samples are analyzed in the incident sites and undergo a preliminary analysis called categorization.

The categorization process has two goals: First, one must perform a quick and rough on-scene assessment of the material using, mainly, nuclear radiation measurement equipment and a non-destructive analysis (NDA) technique (i.e., gamma-ray spectroscopy) to determine the health risk of the seized materials to the first responders, law enforcement personnel, and local population. Also, this process determines the nature of incidents like criminal activity or accidental release. If it involves criminal activity or threats to national security, one must decide on additional steps to take **[*9*]**. Second, one must categorize the interdicted smuggled nuclear materials to assess the threat using NDA techniques such as neutron counting or gamma (γ) spectroscopy, determining the extent of environmental contamination and nuclear proliferation issues.

B. Nuclear Forensic Analytical Plans

Nuclear forensic analytical plans are a laboratory analysis of the physical and chemical properties of the collected or seized nuclear and radioactive materials. It involves the full analysis of nuclear or other radioactive materials to identify some basic parameters or “signatures” like the isotopic composition of uranium (U), plutonium (Pu), and other stable elements (i.e., elemental analysis); the age of the nuclear materials (i.e., radiochronometry); chemical impurities (i.e., trace elements); and organic impurities, macroscopic parameters, and microstructure and physical dimensions to get some clues on the origin and intended use of the materials (Figure 2) **[*2, 4, 5*]**. Nuclear forensic analysis for both nuclear and non-nuclear materials should be done using a model action plan for nuclear forensic analysis (Figure 2). Various physical and analytical chemistry techniques such as visual inspection, optical microscopy, scanning electron microscopy, X-ray spectroscopy, X-ray fluorescence analysis, X-ray diffraction analysis (XRD), Fourier transform infrared spectroscopy, radioactive counting techniques, chemical assay, radiochemistry, radiography, mass spectrometry (MS), inductively coupled plasma mass spectrometry (ICP-MS), gas chromatography-mass spectrometry (GC-MS), secondary ion mass spectrometry (SIMS), etc. are used to characterize the nuclear and radiological materials.

However, a single parameter (signature) and a single analytical technique may not be sufficient to discern the identity and origin of the interdicted nuclear materials. Therefore, the multiple parameters or signatures and the analytical techniques would be used to ascertain the source of the nuclear materials, which eventually supports the precise interpretation **[*2, 4, 5*]**. The steps for nuclear materials characterization are a bit shorter than the complete interpretation steps. To ensure nuclear security, it is a state’s responsibility to set up a nuclear forensics laboratory with complete characterization capabilities or collaborate with another country for sample characterization and interpretation **[*3*]**.

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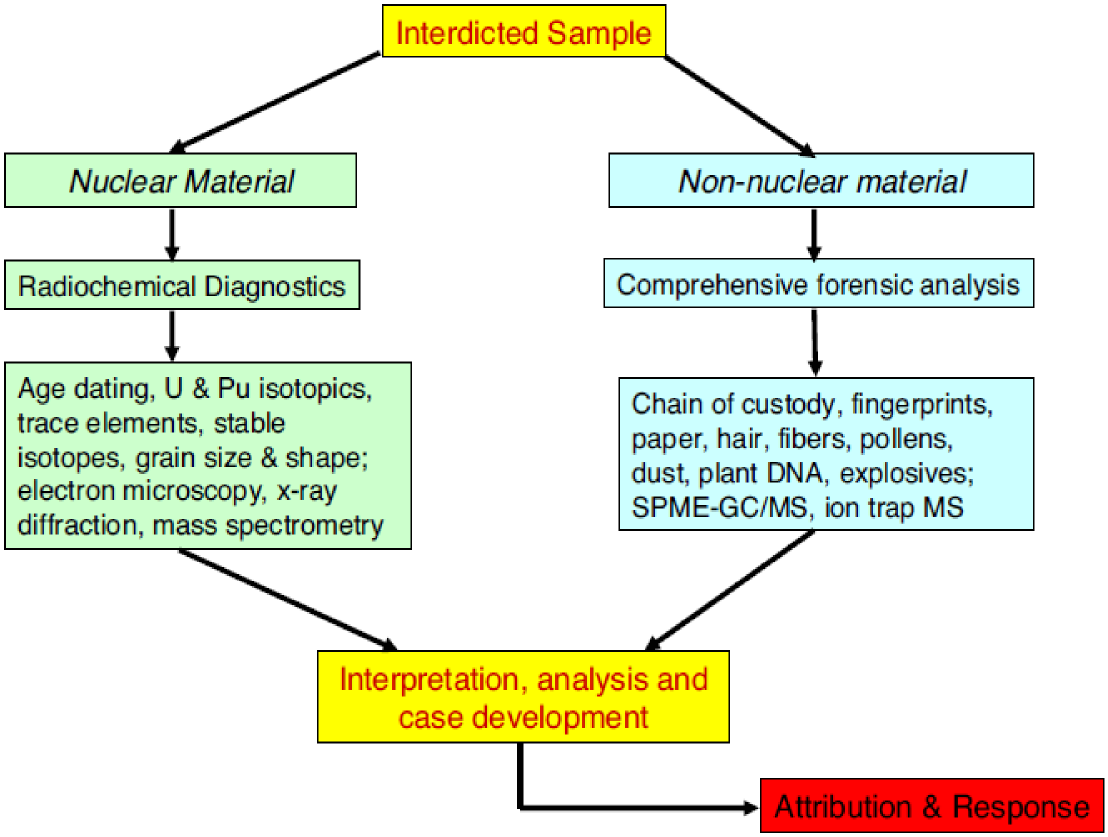

Figure 2. A model action plan for nuclear forensic analysis [*10*]

Nuclear forensic science uses various analytical tools and techniques to detect nuclear and radioactive materials (Table 1). The international nuclear forensics community met with the Nuclear Forensics International Technical Working Group (ITWG) and has achieved consensus on the proper sequencing of analytical techniques (Table 1) to provide invaluable nuclear forensics information as early as possible in the attribution process. The ITWG and IAEA recommend that scientists analyze the nuclear materials having short half-lives and sensitivity to environmental degradation (i.e., HEU residue) within the first 24 hours of interdiction. Non-destructive analysis (NDA) techniques should be used in the first analysis (24 hours) so that the same sample can be used in the subsequent analyses.

Table 1 shows a generally accepted sequence of analysis of nuclear materials after interdiction. The table also provides information about the analytical techniques commonly used within the first 24 hours, after one week, and after two weeks of receiving the sample in nuclear forensics analyses and investigations **[*9, 11*]**.

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Table 1. Laboratory methods and techniques with typical timescales for analyses [3]

Technique/method	Conducted within 24 hours	Conducted within One week	Conducted within 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 and other physical characteristics Scanning electron microscope (SEM) X-ray diffraction	Nanostructure, Morphology and other physical characteristics Transmission electron microscopy (TEM)
Isotope analysis	High-resolution gamma-ray spectrometry (HRGRS)	Thermal ionization mass spectrometry (TIMS) Inductively coupled plasma mass spectrometry (ICP-MS)	Secondary ion mass spectrometry (SIMS) Radioactive counting techniques (α and γ spectrometry)
Radiochronometry	High-resolution gamma-ray spectrometry (HRGRS) for Pu	Thermal ionization mass spectrometry (TIMS) Inductively coupled plasma mass spectrometry (ICP-MS)	High-resolution gamma-ray spectrometry (HRGRS) for U α spectrometry Gas chromatography-mass spectrometry
Elemental/chemical composition	X-ray fluorescence	Inductively coupled plasma mass spectrometry (ICP-MS) Chemical assay Fourier transform infrared (FTIR) X-ray spectrometry Isotope dilution mass spectrometry (IDMS)	
Traditional forensic analysis	Collection of evidence associated with traditional forensics such as blood, fingerprint, insects, plastic, etc.		Analysis and interpretation of evidence associated with traditional forensics

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III. Characteristic Parameters

The characteristic parameters or "signatures" found in nuclear materials reveal the origin of the materials **[*4*]**. Analyzing seized nuclear materials for nuclear forensics can be performed in any materials characterization laboratory. However, a specialized facility for testing a radioactive sample with a highly skilled technician is found only in designated nuclear forensics laboratories and nuclear research laboratories. Nuclear forensics technicians need special precautions to handle and analyze nuclear or radioactive samples. They also need radiation safety training, protective gear, and personal protective equipment (PPE).

Once a lab receives the seized materials, the analyses are performed using the nuclear forensic examination plan (Figure 1) and the nuclear forensics analytical plan (Figure 2 and Table 1). The designated lab should have a well-developed analytical facility and operational procedures designed to minimize cross-contamination during the analysis. A combination of the analytical techniques is used to ensure data accuracy to determine their signatures. Furthermore, the results of nuclear forensics would be the legal prosecution. In addition, the results reflect the national and regional security and possible military retaliation against criminals.

Therefore, the characterization of the seized nuclear materials must be done carefully and in a well-documented manner. This includes the cross-calibration analysis (QA/QC), a choice of specific and high-purity reference materials, and demonstrated competencies in the analysis. Also, if possible, the analysis of the same materials must be done in multiple labs and must compare the data to ensure accuracy **[*7*]**. The following types of nuclear forensics "signatures" are generally used to answer the questions of a law enforcement agency and during the legal prosecution in national and international courts.

A. Physical Characterization

In a nuclear forensics examination, the physical dimension (i.e., diameter, height, and weight) analysis technique is one of the first to characterize the nuclear materials. The reason is that the seized nuclear materials' size and shape can provide essential clues about the materials' origin and transportation routes. This technique is instrumental in identifying the nuclear fuel pellets. The nuclear reactor's fuel pellets are made by compacting uranium dioxide (UO_2) powder; some reactors use enriched uranium, and some use natural uranium pellets as fuel.

The fuel pellets' shape, size, enrichment levels, and structure vary by reactor type. For example, the dimensions of Heavy Water Reactor (HWR) and Pressurized Water Reactor (PWR) fuel pellets are different. Some reactors pellets have a central hole that provides space for gaseous fission products during irradiation processes. Those characteristics are observed in a nuclear forensics analysis to find the material's origin and history. For instance, in 2003, four uranium fuel pellets seized in Lithuania were analyzed at the Institute for Transmutation Elements (ITU), Karlsruhe, Germany. The fuel pellets were cylindrical with a central hole and one concave face. Based on the physical dimensions and enrichment levels, a nuclear forensics technician identified that the uranium fuel pellets were from an RBMK – 1500 nuclear reactor (i.e., graphite-moderated, water-cooled Russian nuclear reactor) **[*2*]**.

B. Radiochronometry (Nuclear Archeology)

In nuclear forensics, when the nuclear materials are purified or enriched and subsequently analyzed, it is called its age **[*4, 12*]**. The shape, size, and age of uranium pellets and other nuclear materials and their enrichment levels and isotopic ratios indicate the origin and history of nuclear materials of historical interest. This branch of nuclear forensics is called radiochronometry or nuclear archeology. These signatures are useful for identifying the age and type of nuclear materials of historical interest. For instance, an old glass jug was recovered from the waste trench at the Hanford site in Washington State, USA. And the Pacific Northwest National Laboratory (PNNL) researchers used radiation counting

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techniques (i.e., gamma spectroscopy and alpha spectroscopy)—and other precise mass spectrometric techniques like Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Gas Chromatography-Mass Spectrometry (GC-MS), and Ion Chromatography (IC)—to identify the origin and age of the nuclear material. For age determination, first, they separated the ^{235}U and ^{239}Pu using Ion Exchange Chromatography (IEC) and then analyzed the isotopic ratios using ICP-MS. ^{239}Pu and ^{235}U are not stable isotopes. ^{235}U is formed through the decay of ^{239}Pu, the half-life of which is 24,110 years.

On the other hand, the half-life of ^{235}U is extremely long (704×10^6 years), and the long half-life of ^{235}U and the subsequent decay of ^{235}U can be ignored for the radiochronometric analysis **[*7*]**. It is assumed that the separation of ^{235}U and ^{239}Pu was complete using Ion Exchange Chromatography (IEC). The time since the last separation is calculated by

$$\frac{N(235_U)}{N(239_{Pu})} \approx \lambda_{239}$$

The time (*t*) since the separation is given by

$$t \approx \frac{\frac{t1}{2} N(235_U)}{ln2N(239_{Pu})} \approx 3.478 \times x10^4 \frac{N(235_U)}{ln2N(239_{Pu})}$$

Other isotopes ratios used for determining the age of uranium materials are $^{235}U/^{231}Pa$ and $^{234}U/^{230}Th$ **[*7*]**. From the above time (*t*) calculation, it was revealed that the sample was 61.6 ± 4.5 years old. They compared the database after the isotopic analysis. They found that the plutonium (Pu) composition was similar to the plutonium (Pu) prepared at the X-10 reactor in Oak Ridge, Tennessee, which was brought to the Hanford T-Plant site for separation. The T-Plant was the world's first industrial-scale Pu reprocessing facility, where the first human-made Pu was separated, and the recovered Pu was the oldest human-made Pu in the world. At the same time, the trace element impurities in the sample were similar to the bismuth phosphate process used at that time to extract Pu from the irradiated uranium. The age of Pu, isotopic composition, and trace element impurities provided sufficient information to determine the origin of the materials in the bottle **[*2, 13*]**.

C. Uranium Isotope Ratios

Uranium ore is mined and milled to produce Uranium Ore Concentrates (UOCs), often called yellowcake. UOCs have a natural isotopic abundance of ^{235}U (0.72%), ^{238}U (99.2%), and ^{234}U (about 53 – 55ppm) **[*2*]**. However, the terrestrial $^{235}U/^{238}U$ ratio varies over a range of 1.3% in different geologic materials **[*14, 15*]**. Therefore, the $^{235}U/^{238}U$ signatures in the UOCs from each site (i.e., geologic environments) or region are distinct. When all three isotopic ratios are considered, no two samples have the same isotopic composition **[*14, 15*]**.

These regional isotopic variations are utilized as a possible forensics signature for nuclear materials. For instance, the three isotopic ratios (^{238}U, ^{235}U, and ^{234}U) of UOCs from Canada have more distinct signatures than the UOCs from Australia and the Middle East **[*14, 15*]**. So, if the interdicted nuclear materials' (UOCs) isotopic ratios are analyzed and compared with the international databases or nuclear forensics libraries, the origin of the material can easily be identified. For instance, two ($K_2(UO_2)3O_4 \cdot 4H_2O$ and $UO_3 \cdot 2H_2O$) power samples (42.9 g of bright yellow and 48.6 g of dark green powder) were seized in Australia, Victoria, by police and analyzed at the Australian National Science and Technology Organization (ANSTO) for the possible compositions of nuclear isotopes. The ^{235}U isotopic ratio was found to be 0.44% and 0.41%, respectively, and the materials also contained ^{232}U and ^{236}U isotopes. However, the ^{232}U and ^{236}U isotopes can be formed by only neutron irradiation in a nuclear

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reactor, and Australia did not have a nuclear reactor at that time. As a result, nuclear forensics researchers concluded that the interdicted materials were from out of the country **[*2, 16, 17*]**.

D. Micro-signatures

The morphological study (e.g., grain size and porosity) was conducted on the two uranium (U) power samples (42.9 g of bright yellow and 48.6 g of dark green powder) seized in Victoria, Australia **[*16*]**. In a scanning electron microscope study, these two samples' grain size and porosity were entirely different. The samples' microstructures depend on the material processing methods, uranium mills, and geographical locations. From these materials' micro-signatures, nuclear forensics researchers determined that those nuclear materials were not only from outside the country but also from two different sources. In addition, they used nanoscale secondary ion mass spectrometry (nanoSIMS) and radiochronometry to ensure the origin of the two seized nuclear materials **[*2, 5, 17*]**.

E. Trace Element Impurities or Rare Earth Elements

Trace elemental impurities or presence of Rare Earth Elements (REEs) in nuclear materials, or UOCs are source inherited. These elements' concentrations change little during the nuclear fuel cycles. Therefore, these elemental impurities or REEs have proved helpful as the nuclear forensics signatures for several seized nuclear materials. Each country's REEs signature is distinct; thus, the seized nuclear materials are analyzed to determine the origin of the nuclear materials. For example, Canada, the USA, Spain, Turkey, and Kazakhstan have distinct REEs signatures. For instance, nuclear forensics scientists analyzed the $^{235}U/^{238}U$ signature to determine the origin of the material (3 kg of radioactive wet brownish-yellow powder) discovered in a scrap metal shipment in Rotterdam Harbor, the Netherlands, in 2003. However, they could not find any database to interpret their data to determine the origin of the material. As an alternative to this method, they analyzed the trace elemental impurities (Al, Ca, Cr, Fe, Mg, Mo, Ni, and P) in the nuclear material and compared them with the international databases. Finally, the elemental impurities signatures identified that the material originated from the Middle East **[*5, 18*]**.

F. Sealed Radioactive Sources

Orphan radioactive sources and other radioactive materials out of regulatory control are a huge problem for nuclear security. After all, terrorists can use radioactive materials from those sources to make a Radioactive Dispersal Device (RDD)—a "dirty bomb" **[*19*]**. The signatures used to determine the origin of nuclear materials can also be utilized to trace the sources of radioactive materials. Initially, a non-destructive analysis technique, such as gamma (γ) spectroscopy, can be used to identify the origin of the radioactive sources. As explained in "uranium isotope ratios" (Section 3C), the mass spectrometry techniques are used to determine the isotopic and elemental compositions. That information can be used to determine the age and origin of radioactive sources. Besides elemental composition and isotopic ratios, a device serial number, logo, and detail specification sheet are used to compare these data with the source licensing database **[*2*]**. To identify the origin of sealed radioactive sources, each country has its own incident register system (IRS). For instance, Canada has the Sealed Source Tracking System (SSTS), an electronic add-on to the National Sealed Source Registry (NSSR), which provides licensees a more convenient and efficient way to report any movement of sealed sources **[*20*]**. CNSC also publicly reports lost and stolen sources, where the lost and found sealed radioactive sources are up to date **[*21*]**. Similarly, Australia has the Australian Radiation Incident Register (ARIR), where information about the missing/stolen and found radioactive sources are available **[*22*]**. These incident registers are vital for controlling and tracing radioactive sources out of regulatory control. Each country should register the lost or stolen sealed radioactive sources in the Incident and Trafficking Database (ITDB) and work with the ITWG and IAEA to identify the missed or stolen radioactive sources **[*2*]**.

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G. Traditional Forensic Evidence

Nuclear forensics focuses not only on the analysis of the nuclear materials but also on the biological materials contaminated with radionuclides or the biological materials found along with the interdicted smuggled nuclear materials. The materials that interest nuclear forensics scientists are DNA, blood, fingerprints, electronic devices, fibers, insects, etc. Despite the high ionization radiation (IR) exposure, these materials still have forensics values and should be examined during the nuclear forensics examination and source determination step. For instance, in the two-uranium powder K2 $(UO_2)3O_4{\cdot}4H_2O$ and $UO_3{\cdot}2H_2O$) samples seized in Australia, Victoria, one sample had a moth body and a detached head along with the samples **[*16*]**. The moth species was studied by entomologists and revealed that the moth species were from outside the country. Thus, the biological samples and nuclear materials are essential for determining the source of interdicted nuclear materials **[*5*]** and for nuclear security.

H. Non-nuclear Materials for Nuclear Forensics

In 1997, a scrap metal piece with some radioactivity was found in Germany. Their preliminary analysis revealed that the traces of fission products (i.e., UO_2 particles) were attached with the metal piece. The elemental analysis (i.e., characterization) found that the metal was stainless steel, which originated from Eastern Europe or Russia. The physical dimension of the stainless steel matched with the upper and middle parts of the fuel assembly of the BN-600 reactor and a BR-10 research reactor **[*2*]**. Similarly, other non-nuclear materials seized along with the nuclear materials help determine their origin, history, and trafficking routes.

IV. Data Interpretation and Attribution

As per the nuclear forensics examination plan (Figure 1), data interpretation is next once the nuclear materials analysis is complete. The data interpretation to trace the origin of nuclear and radiological materials depends on the availability of similar data. Thus, data interpretation is lengthy and complicated in a nuclear forensics examination plan.

There are several steps for data interpretation and source attribution. First, data quality is paramount. High data quality can be achieved through a well-equipped lab, highly skilled technicians, high-quality assurance, and quality control (QA/QC) procedures, as well as a high purity reference material, to check the instrument's accuracy, precision, and reproducibility. Second, data interpretation involves correlating analytical data or comparing similar data within the country and internationally. Therefore, the databases available for comparison are vital in this process. A national forensics laboratory, a national forensics library, and data sharing among states are instrumental in interpreting the samples. Third, open and closed literature can also be used for data comparison and interpretation. Fourth, each country with a civilian nuclear power program should set up a national forensics laboratory, associated databases of nuclear fuel cycle processes, and a forensics library of all the materials used, produced, stored, and imported from another country. Also, each country should have its own incident register system (IRS) and collaborate with the nuclear forensics International Technical Working Group (ITWG), Incident and Trafficking Database (ITDB), and IAEA for data sharing and interpretation. Fifth, interpreting and attributing the nuclear materials out of regulatory control, if available, uses multiple nuclear signatures to ensure the accuracy of the origin, history, and trafficking routes of the illicitly trafficked nuclear materials. Sixth, one must use a combination of forensics techniques to analyze the nuclear materials for nuclear attribution and interpretation. Finally, data interpretation should be done using a deductive and iterative process, as each successive comparison may provide more precise information about the nuclear materials **[*3*]**.

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V. Conclusions

The illicit trafficking of nuclear materials is one of the most severe threats to global nuclear security and stability. The international community recognized that nuclear forensics could effectively determine the origin of detected nuclear and radioactive materials and control illicit nuclear trafficking and nuclear terrorism. Nuclear forensics science utilizes the unique signatures (i.e., physical properties, isotopic ratios, radiochronometry, trace elemental impurities, and traditional forensics) present in the nuclear and radiological materials to determine their origin, history, and transportation routes. Consequently, it was recognized as one of the essential components of nuclear security and safeguards.

However, to take full advantage of nuclear forensics—in the fight against nuclear smuggling and terrorism—one must consider its requirements. It calls for a robust nuclear forensics capability, high-quality data from a well-equipped laboratory, relevant databases or a nuclear forensics library, specialized skills and knowledge to interpret the data, and international cooperation in technology and human resource development. Since nuclear forensics is based on scientific evidence and facts, the final data obtained from the nuclear forensics analyses are valid before a national and international court of law for legal prosecution. To this end, it deters illicit nuclear trafficking and nuclear terrorism. That is why it is one of the most important nuclear security and safeguards tools.

Additionally, a well-developed nuclear forensics program is an integral part of a robust nuclear security regime for a civilian nuclear energy program and a vital element of a country's nuclear security infrastructure. Based on nuclear incidents, pre- and post-detonation forensics analyses are used for determining the source of the nuclear materials for legal prosecution. In pre- and post-detonation nuclear forensics, nuclear forensics scientists, a law enforcement agency, and the national intelligence agency collaborate to answer questions related to the origin, history, impacts on human health and the environment, and other national nuclear security threats from terrorists and criminals.

Most nuclear or radiological materials contain multiple signatures. Sometimes a single nuclear signature is enough to ascertain the source of the illicit nuclear or radioactive materials. Sometimes, various nuclear signatures are necessary to determine the exact source of the nuclear materials out of regulatory control. However, nuclear signatures of the interdicted nuclear materials are helpful to determine the origin and history of the materials only if the databases (i.e., signatures) are available for comparison and interpretation. Therefore, one of the critical parts of nuclear forensics examination is the data available for comparing the nuclear forensics lab data with the national and international databases. That is why effective nuclear forensics relies on cooperation between national and international partners for data sharing and interpretation. In addition, a complete nuclear forensics analysis involves, of course, the analysis (i.e., both physical and chemical) of the nuclear or radioactive materials, as well as any biological or non-nuclear materials contaminated with radionuclides (i.e., traditional forensics). This process determines the sources and history of nuclear materials. Most importantly, nuclear forensics is the key to identifying weaknesses in a physical protection system and nuclear material accounting. Once identified, these weaknesses can be corrected by taking the necessary measures. Therefore, nuclear forensics can be an integral part of nuclear safety, security, and safeguards and can be applied to reduce the illicit trafficking of nuclear materials.

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