
10-2023

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Recommended Citation

Dion, Heather M.; Fox, Caterina; Knight, Kim; and Phillip, Anne (2023) "Women as a Force Multiplier for Bringing Nuclear Forensic Capabilities to the International Stage," *International Journal of Nuclear Security*. Vol. 8: No. 2, Article 14.

<https://doi.org/10.7290/ijns613664>

Available at: <https://trace.tennessee.edu/ijns/vol8/iss2/14>

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Cover Page Footnote

Dedication The authors would like to dedicate this publication to Ian Hutcheon (1947–1915), who served as senior technical advisor, mentor, and friend to so many across the nuclear forensic community. His dedication and passion in the early years of the program helped define the technical exchanges and capability building that grew NNSA's international outreach from just a few partners to over a dozen within a mere 5 years. Ian served as mentor to an entire generation of nuclear forensic practitioners, supporting national security through scientific excellence. His legacy lives on through the continued successes of his students and proteges. **Acknowledgements** The rapid growth of the INFC program would not have been possible without the dedication and hard work of dozens of people. Specifically, the authors greatly thank Ambassador Laura Holgate, Major General (ret.) Julie Bentz, Dr. Frank Wong, Dr. David Smith, Michael Curry, Dr. Stephen LaMont, Wayne Mei, and Ed Fei, without whom this fledgling NNSA outreach program would never have had the success it achieved in less than a decade. The INFC program lives on as part of NNSA's Nuclear Smuggling Detection and Deterrence program (NSDD); this article serves as a historical document of the early years of the program and is not intended to direct or imply any actions of the current Investigative Support activities under NSDD.

Women as a Force Multiplier for Bringing Nuclear Forensic Capabilities to the International Stage

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Abstract

In 2009, the US Department of Energy National Nuclear Security Administration's (NNSA's) Defense Nuclear Nonproliferation Program initiated a new nuclear forensics outreach effort under its Confidence Building Measures Program. Little did they know that the timing could not have been better. This article focuses on the early years (2009–2015) of the NNSA's international nuclear forensics outreach, specifically the efforts and experiences of the women who helped establish this program, building it from a fledgling, bilateral effort into an enduring technical capacity provider engaging with dozens of countries and multilateral organizations. At the onset of the program, nuclear forensics was an emerging priority within the US Government and receiving increased focus from international organizations through high-level diplomatic efforts such as the Nuclear Security Summit and Global Initiative to Combat Nuclear Terrorism. Additionally, working-level initiatives were gaining traction through the International Atomic Energy Agency and the Nuclear Forensics International Technical Working Group. Over the next 6 years, a small team comprising a uniquely large number of women NNSA federal, contract, and national laboratory staff served as key leaders engaging with the international community to strengthen global technical nuclear forensics capacity and best practices.

The program continues today under the Nuclear Smuggling Detection and Deterrence Program as Investigation Support. The experiences shared here detail a unique time period when the new technical discipline of nuclear forensics was beginning to mature and gain international traction. The authors have made every effort to remember history

correctly and be as inclusive as possible. A wealth of training, guidance, and exercise documentation was developed in the 2009–2015 time frame, much of which still serves as the foundation for today's even more extensive program and community of dedicated technical and diplomatic practitioners.

Keywords: nuclear forensics, international capacity building

1. Setting the Stage (2009–2010)

In 2009, the subject of nuclear forensic investigations was an emerging priority within the US Government and an increasing focus of international engagement. Over the previous two decades, the world saw a drastic increase in the number of events involving nuclear or radioactive materials out of regulatory control. This trend was generally attributed to the disintegration of the Soviet Union and degradation of the security envelope protecting many nuclear and radioactive materials. The result was an increase in the occurrence of orphaned sources and criminal activity involving the trafficking of illegally obtained nuclear materials. Several of these high-profile cases involved relatively small quantities of materials (e.g., 5 g of highly enriched uranium [HEU] interdicted in Rousse, Bulgaria, or 2 g of HEU interdicted in Paris, France in 2001) [1]. However, a few incidents involved significantly higher quantities. For example, 2.7 kg of HEU was recovered by police in Prague, Czech Republic, in 1994 [1], and police recovered 3.0 kg of HEU in St. Petersburg, Russia, in 1994 [1]. These and other cases led the United States to recognize the potentially serious consequences associated with nuclear material out of regulatory control and, in response, initiated numerous global nuclear security initiatives. In addition to improving nuclear material accountancy, physical security, and radioactive material detection at borders, there was a recognized need to ensure a proper response to these interdictions that included legally defensible forensic examinations and provenance assessments. The United States supported a number of efforts that emphasized nuclear forensics as a key part of a comprehensive approach to nuclear security, including the International Atomic Energy Agency (IAEA) Office of Nuclear Security's Nuclear Security Series Documents, Nuclear Forensics International Technical Working Group (ITWG), Poneman-Kiriyenko Nuclear Energy and Security Working Group [2], Global Initiative to Combat Nuclear Terrorism, and the Joint US–Japan Statement toward a World without Nuclear Weapons [3]. Motivating this engagement was the construct that strengthened global technical nuclear forensic awareness, response, and best practices could serve as a powerful deterrent to prospective proliferators. Governments could use nuclear forensics techniques to bolster international action against illicit trafficking by identifying material protection control and accounting failures, using technical evidence to support prosecutions, and investigating smuggling networks [4].

Foundationally, the international nuclear forensics outreach program grew from proliferation prevention efforts and focused on the forensics of predetonation materials routinely recovered from outside of regulatory control since the early 1990s rather than postdetonation forensics associated with the terrorist use of a nuclear weapon. A primary goal was to disseminate best practices for the forensic examination of interdicted materials from throughout the nuclear fuel cycle by employing a range of

analytical techniques to determine the material's physical and chemical characteristics (e.g., color, density, major and trace element compositions, isotope abundances, and model age) and assessing signatures that answer investigative questions or contribute to a provenance assessment. The program engaged foreign partners across a wide spectrum of activities that contribute to successful forensic examinations, including enhancing capacity to characterize and identify nuclear materials; understand signatures and knowledge management; handle, store, and transport samples safely and within a chain-of-custody; and comparison of nuclear forensic data with known signatures of nuclear and radiological materials. The results of these efforts are manifest through the enduring bilateral technical contributions to the field, the revitalized national prioritization across the globe on the examination of materials found out of regulatory control, investigating and prosecuting illicit activity, and increasing numbers of practitioners in the field as measured by the incorporation of nuclear forensics into national-level nuclear security programs, participation in multilateral nuclear forensics activities, university programs, international conferences, and journal articles.

At the forefront of developing the National Nuclear Security Administration (NNSA) vision was Anne Phillips, who, through experience leading bilateral and multilateral nuclear nonproliferation capacity-building programs, recognized the emerging need and was well-positioned within NNSA to understand the opportunity to leverage existing bilateral interactions in safeguards, export controls, and nuclear security. Nuclear forensic practices were already well-developed in the United States, with roots stretching back to the early days of nuclear testing and concerted recent developments in nuclear fuel cycle materials characterization methods in the 1990s and 2000s. Phillips arranged for a number of US Department of Energy (DOE) NNSA laboratory subject matter experts actively involved in material characterization projects for other offices, including Ian Hutcheon, David K. Smith, Mike Kristo, and Kim Knight from Lawrence Livermore National Laboratory and Heather Dion, Stephen LaMont, and Robert Steiner from Los Alamos National Laboratory. This team and their coworkers leveraged existing projects supporting uranium ore concentrate characterization, analytical work in support of the IAEA Network of Analytical Laboratories, and collaborations being built up through the ITWG to help develop and launch the new NNSA-lead program focused on international nuclear forensic engagement.

In 2009, it became clear that NNSA would need a full-time technical advisor to support the growing program; Heather Dion, an analytical chemist with experience in international engagements, was asked to directly support NNSA Headquarters (HQ) through a change-of-station assignment from Los Alamos National Laboratory. During those first few years, Dion helped develop the technical foundation of the program and interface across NNSA and the US interagency to ensure that NNSA's developing program was unique and complementary to other outreach and capacity-building efforts; she also coordinated with interagency nuclear forensics stakeholders. Several Nonproliferation Graduate Student Fellows were also instrumental in helping Phillips and Dion get the fledgling program off the ground, including Lindsey Gehrig, Paula Alfonso, and Annie Winterfield. These early days included many hours coordinating with US Department of State's (DOS's) Weapons of Mass Destruction Terrorism Office, who

led many international nuclear forensics efforts, as well as NNSA Counterterrorism and Counterproliferation's Consequence Management Office, who led domestic predetonation forensics operational work.

Through consultation with subject matter experts (SMEs) and interagency stakeholders, NNSA's Office of Defense Nuclear Nonproliferation (DNN) Office of Nonproliferation Policy and Arms Control developed a vision for enhanced international nuclear forensic cooperation. An initial goal was the development of state capacities to characterize materials and interpret chemical, physical, and isotopic signatures of nuclear materials to support the attribution of illicitly trafficked materials to the originating facility or to exclude specific countries or facilities from consideration. Initial international outreach efforts were scientific in their nature, focusing on nuclear material measurements and signature recognition, leaving eventual attribution to law enforcement, internal security, or regulatory authorities within a state. These early engagements would gain traction serendipitously through the upcoming Obama Administration Nuclear Security Summit process.

a. President Obama's Nuclear Security Summits

The Obama Administration focus on nuclear security and raised awareness across the global stage to support and accelerate nuclear security practices, including HEU use minimization efforts, enhanced nuclear detection, increased physical security and law enforcement, and the development of nuclear forensic capabilities. The Obama Administration's vehicle for enhancing nuclear security was through a novel series of summits where invited countries would develop best practices as a community, as well as statements pledging individual actions to implement those best practices.

In the inaugural Nuclear Security Summit, a format was developed where commitments at the unilateral and individual state levels were made to strengthen nuclear security practices through communiques and state declarations. The 2010 Nuclear Security Communiqué specifically called out for participant nations to "effectively prevent and respond to incidents of illicit nuclear trafficking; and agree to share, subject to respective national laws and procedures, information and expertise through bilateral and multilateral mechanisms in relevant areas such as nuclear detection, **forensics**, law enforcement, and the development of new technologies" [5]. Additionally, Japan, Thailand, and the United States developed pledges specific to the development of nuclear forensic capabilities. These pledges eventually grew into some of the first bilateral engagements under the new NNSA Capacity Building Program that would soon be known as the International Nuclear Forensics Engagement Program (INFC).

b. Interagency Coordination and Multilateral Engagement

To successfully execute the INFC, a new international outreach program using nuclear forensic engagement to support nuclear nonproliferation, it was essential to coordinate closely with existent US organizations such as the Forensics Engagement Working Group (FEWG) coordinated by the DOS [6]. The FEWG served as an interagency clearinghouse for nuclear forensics requests from international partners and a

coordinating body for US outreach to foreign partners. They received requests for support with nuclear forensic investigations, nuclear materials characterization, and legislative workshops to help support the development of laws to prosecute nuclear trafficking incidents. The FEWG was also the main interlocutor for multilateral nuclear forensic efforts, including coordinating participation with the IAEA Office of Nuclear Security, the Nuclear Smuggling ITWG, and the Global Initiative to Combat Nuclear Terrorism (GICNT). NNSA's INFC quickly demonstrated the value of involving national laboratory technical SMEs supporting a range of nuclear material characterization projects to development of productive, technically-based collaboration. US participation of SMEs encouraged meaningful scientist-to-scientist engagement; effective appraisal of the unique technical strengths, needs, and challenges facing different international partners; and helped identify additional needs (e.g., law enforcement and/or policy development support) that the interagency could support. An interesting side note is that for almost a decade, the FEWG was chaired by women, including Aryn Weinberg, Sara Friendrich, and Daniella Helfet from DOS.

c. Coordination within NNSA

Multiple offices within DNN and the Office of Counterterrorism and Counterproliferation already held strong bilateral relationships with potential INFC partner countries. Close coordination within NNSA was essential to not overwhelm partners while developing the program framework. Partner countries were often operating with constrained resources and efficient configurations of agencies and specialists focused on the full range of nuclear activities. As a result, different programs within DNN could end up in competition for limited resources within a partner's nuclear regulator, technical laboratory, or law enforcement organization while working partnerships to improve nuclear security, emergency response and consequence management, safeguards, and nuclear forensics capabilities. This competition resulted in the development of an informal coordination group among DNN outreach organizations across the DNN offices. Additionally, during that time frame, DOE NNSA organizations involved in nuclear forensics (both to support domestic and international activities) found it beneficial to coordinate activities, which lead to the formation of a DOE NNSA committee on nuclear forensics. The group identified a number of internal actions that helped solidify nuclear forensic practices within DOE NNSA, including the development of classification guidance, prioritization of technical investments, supporting and staffing IAEA requests, identifying needs in standard reference materials, and coordinating the timing of bilateral engagements.

d. Initiating International Engagements

Developing the first few engagements was strategic in nature; NNSA already had close collaborations with a number of countries in the areas of nuclear safeguards, weapons of mass destruction export controls, and nuclear security. Most of these engagements were covered under bilateral nuclear cooperation agreements at the ministerial level; the incorporation of nuclear forensics under these agreements allowed for direct scientist-to-scientist engagement to quickly begin using established government-to-government protocols and execution plans such as Action Sheets to document the exact technical work to be accomplished. The technical scope for the first several Action

Sheets was largely negotiated by Heather Dion as an offshoot of previous work done under environmental safeguards Action Sheets with France and Japan. Additional Action Sheets were negotiated under the European Commission Euratom (European Atomic Energy Community) agreement with the Joint Research Center for Transuranium Elements. These initial projects were the foundation for further growth.

Another avenue for engagement was through the Science and Technology Center in Ukraine and International Technology Center with Ukraine, Uzbekistan, and Kazakhstan. These interactions were initially offshoots of prior cooperative threat reduction work in nuclear security. The interactions with Ukraine evolved to include additional nuclear material characterization through Kim Knight's historic relationship with Ukrainian nuclear institutes. The interactions grew through INFC to include nuclear forensic material characterization training, development of national nuclear forensics libraries, and material exchanges in the work scope.

During these early days, the amount of travel was overwhelming. Even if many of the initial partners were well-known to the SMEs, the negotiating of work under existing agreements still required extensive face-to-face meetings to build an understanding of how technical cooperation could support nuclear forensic investigations, help facilitate meetings between scientific and law enforcement communities to create coordinated responses to materials found out of regulatory control, and to develop the specific technical projects that would advance the science of nuclear forensics.

2. Nuclear Forensic Gains on the International Stage (2012–2014)

As nuclear forensics gained momentum as a national priority and distinct technical discipline, so did the growth in capability providers across government, including law enforcement. Discrete impacts were made by a number of organizations, and these individual contributions built into the paradigm of a whole-of-government approaches to nuclear forensic investigations and subsequent prosecution of illicit traffickers of nuclear materials. Table 1 demonstrates how efforts at all levels of government supported integrated nuclear forensic capability development in support of nuclear security. INFC SMEs were key contributors during this time frame, supporting policy development, awareness workshops, exercises, guidance documents, scientific exchanges, and training courses across all four of the organizations during this time of rapid evolution in nuclear forensic awareness across the globe.

Table 1. Key international organizations championing nuclear forensics capability development

Organization	Audience	Time frame	Outcomes
Nuclear Security Summit [5]	Presidential/Prime Minister level	2010–2016	Awareness raising at the highest levels of government, including commitments to sign and ratify international agreements
GICNT [7]	Ministerial representatives, policymakers	2006–2022 (suspension owing to Russia–Ukraine conflict)	Development of practical policy and communication documents for ministerial-level officials
IAEA [8]	Policymakers to technical contributors	2006–present	Guidance documents, training, and practitioner opportunities in the area of nuclear forensics
ITWG on Nuclear Forensics [9]	Technical contributors	1995–present	Peer-to-peer engagement, laboratory, law enforcement, and provenance assessment best practices and exercises

a. 2012 Nuclear Security Summit

In March 2012, the second Nuclear Security Summit was held in Seoul, South Korea. Representatives from 53 nations (up 6 from 2010) convened to report on progress and renew pledges to increase global nuclear security. Nuclear forensics was now becoming part of the international nuclear security lexicon and was once again highlighted in the Summit’s Communiqué:

We recognize that **nuclear forensics** can be an effective tool in determining the origin of detected nuclear and other radioactive materials and in providing evidence for the prosecution of acts of illicit trafficking and malicious uses. In this regard, we encourage States to work with one another, as well as with the IAEA, to develop and enhance **nuclear forensics** capabilities. In this regard, they may combine the skills of both traditional and **nuclear forensics** through the development of a common set of definitions and standards, undertake research

and share information and best practices, as appropriate. We also underscore the importance of international cooperation both in technology and human resource development to advance **nuclear forensics** [5].

In addition to the Communiqué, national commitments were made by Australia, Canada, Czech Republic, France, Georgia, Germany, Japan, India, Israel, Netherlands, Morocco, Pakistan, South Korea, Singapore, Spain, Sweden, Switzerland, Thailand, Turkey, Ukraine, United States, and Vietnam. These commitments included pledges to improve legislation necessary to prosecute nuclear trafficking, develop law enforcement and forensic laboratory capabilities, and participate in international capacity-building activities. Additionally, several of these participant countries credit for hosting and/or attending workshops facilitated by the INFC program, as well as INFC supported activities with the GICNT and IAEA [5].

b. Expanded Partnership with the IAEA (2011–2013)

As the INFC program was starting to take shape with identified strategies for engagement across a wide range of partner technical capability, the IAEA was also expanding their expertise and focus on nuclear forensics. Prior to 2010, the IAEA had a single technical document on nuclear forensics (Nuclear Security Series #2: *Nuclear Forensics Support* [4]), which was prompted by the recognition that additional information gleaned from material characterization could support the investigation of reported cases of nuclear trafficking. Questions to elucidate where the material was obtained, what was its intended use was, and if a seizure was related to other seizures of materials in the past are discussed in Nuclear Security Series #2. The idea that nuclear forensics is a combination of scientific and law enforcement investigations is also discussed. This document is the first time the idea of a “Model Action Plan” is discussed, which helps guide the type and timeline of specific chemical and physical characterizations that may help answer outlying questions regarding the material. The “Model Action Plan” was based on a publication from the Nuclear Forensics ITWG (formerly Nuclear Smuggling ITWG) [10]. The ITWG and its role in forwarding the adoption of international nuclear forensics norms will be discussed further in a following section.

In addition to the development of guidance documents, the IAEA also began supporting technical advances in nuclear fields through the Coordinated Research Projects (CRP) program. The first nuclear forensics CRP ran from 2008 to 2012 and consisted of seven member states undertaking research to forward nuclear characterization and investigation topic. The result was the publication of TECDOC #1730, *Application of Nuclear Forensics in Combatting Illicit Trafficking of Nuclear and Other Radioactive Material* (2013) [11].

In addition to supporting the development of guidance documents and CRP activities, INFC approached the IAEA about developing a series of training courses for member states. The first international Nuclear Forensics for Practitioners course was held cooperatively between INFC and the IAEA in 2012 and provided hands-on training, employing a realistic scenario. This course walked participants through a nuclear

forensics investigation, including sample receipt, chain of custody, material identification, collection of traditional forensic evidence (e.g., fingerprints, fibers), development of a sample analysis plan, and the conduct of initial physical characterization and radionuclide identification using gamma and alpha ray spectrometry. This course continues today, now called Nuclear Forensics Methodologies, and remains a benchmark for hands-on nuclear forensics training.

A key finding from the first Practitioners course was that although in many instances technical nuclear material characterization capabilities existed within national nuclear technical institutes, those practitioners were not involved in the legal prosecution involving nuclear materials found out of regulatory control. To provide awareness to the various departments, agencies, and ministries involved in nuclear trafficking, the IAEA (with support from the European Union Joint Research Center Institute for Transuranium Elements, the Australian Nuclear Science and Technology Organization, and the US INFC) developed an Introduction to Nuclear Forensics training course aimed at policy- and decision-makers within member states. This course did not have the same hands-on components of the Practitioners course but did maintain some of the scenario components through tabletop exercises. This course allowed the content to be delivered in far many more places and reach a broader audience.

Through the deployment of the Practitioners course and introduction workshop, as well as querying member states on what additional guidance documentation was needed, the IAEA served as a major force in the codification of nuclear forensics as part of a nuclear security regime during the 2011–2013 time frame.

c. Global Initiative to Combat Nuclear Terrorism

The GICNT was chartered in 2006 and cochaired by the United States and Russia as a multilateral capacity-building organization to prevent, detect, and respond to nuclear terrorism [7]. GICNT represents 88 partner nations and 5 international organizations dedicated to increasing “partnership capacity to combat nuclear terrorism on a determined and systematic basis, consistent with national legal authorities and obligations they have under relevant international legal frameworks, notably the Convention for the Suppression of Acts of Nuclear Terrorism [12], the Convention on the Physical Protection of Nuclear Material and its 2005 Amendment [13], [and] United Nations Security Council Resolutions 1373 and 1540” [14, 15]. The Implementation and Assessments Group of the GICNT identifies areas for investment and initiates working groups to focus on specific topical areas of interest to the partners. In 2012, a Nuclear Forensics Working Group (NFWG) was formed to “raise awareness of nuclear forensics among policymakers; develop guidance and conducting supporting activities; assist partners to develop and sustain nuclear forensic capabilities; foster intra- and intergovernmental relationships; and promoting exchange of best practices in nuclear forensics” [16]. Over the next few years, the GICNT NFWG developed a best practices document, held several workshops to raise awareness about the need for intergovernmental coordination, and developed a self-assessment tool available to partners to help guide the investment of resources dedicated to nuclear forensics and investigative support.

d. International Working Group on Nuclear Forensics

The International Working Group on Nuclear Forensics was founded in 1995–1996 as the Nuclear Smuggling ITWG as an initiative of the G8. The working group initially comprised scientists from DOE national laboratories, the European Union Joint Research Center Institute for Transuranium Elements, and European country nuclear technical laboratories. The ITWG's focus is to advance the scientific discipline of nuclear forensics through the development of best practices and to establish a standardized, worldwide approach to technical nuclear forensics. The ITWG addresses these goals through task groups focused on communications, outreach, and training; evidence; exercises; guidelines; and national nuclear forensics libraries. Specific activities have included crime scene evidence-handling exercises, nuclear material characterization and development of model action plan guidelines, sample analysis round-robin opportunities, and virtual national nuclear forensics library exercises.

The growth of ITWG membership in the 2011–2013 time frame demonstrated the demand for additional technical opportunities to exchange best practices for evidence collection and forensic examinations, participation in sample analysis and national nuclear forensics libraries exercises, and creating stronger ties between the technical and law enforcement communities. INFC SMEs have chaired and cochaired a number of the working groups and contributed to many of the exercises, guidelines, and workshops sponsored by the ITWG.

e. Building the INFC Program: Developing the Program and Engagement Strategies

By mid-2010, the fledgling INFC program was starting to take shape with a few tentative bilateral engagements underway, and an engagement strategy was needed to prioritize activities. NNSA management recognized that to cement nuclear forensics as part of a nation's overall nuclear security enterprise, they would need to develop engagement strategies that supported existing partner infrastructure and encouraged the development of stronger relationships between nuclear scientists and law enforcement.

The development of a new outreach program brought with it both opportunities and challenges. Very rarely are we on the cusp of being able to define our own destiny and are given the resources to make it happen. Because Phillips and Dion had long histories of developing peer-to-peer and capacity-building nonproliferation programs for NNSA, they were well-positioned to capitalize on the opportunity to develop a technical engagement program for nuclear forensics. Many of the initial forensic engagements were offshoots of other NNSA nonproliferation engagements with advanced partners such as the French, Japanese, and European Commission. The early days of the program were exciting and stressful, and limited staffing often meant traveling multiple weeks and month away from family and the office; however, the result was incredibly fulfilling through the formation of long-term friendships and a shared passion for strengthening international norms in nuclear security.

As the number of engagements expanded, developing a framework became essential for setting priorities and managing the increasing number of bilateral partners. The

framework was tailored to a specific partner country's level of expertise, interest, and capacity. Initially, we based our outreach on a *tiers of engagement* approach to broadly describe three main categories of scientific and technical cooperation under the program. These categories contain activities that require decreasing levels of laboratory technical sophistication in the nuclear forensics arena. Under this approach, a partner state is not formally assigned to a specific *engagement tier*. Each country is unique with respect to fuel cycle technology, analytical laboratory infrastructure, and data interpretation capabilities for nuclear forensics, as well as status regarding nuclear security laws and policies, international nonproliferation treaties, and bilateral agreements with the US Government. Partner countries may therefore participate in multiple activity tiers based on their assessed needs. This a la carte approach to selecting activities ensured we could more efficiently develop a limited set of training curricula, exercises, or laboratory experiments while still allowing for very country-specific engagements directed against their specific requests and capabilities.

The types of cooperative activity falling within the three general categories of engagement generally track with a partner's level of nuclear fuel cycle development. Of course, identified activities under a specific tier may not be appropriate for all countries with similarly developed nuclear fuel cycles, depending on existing experience with nuclear forensics, the ability to accept new capacity, and regional relationships (e.g., reliance on capability of a neighboring country).

Tier I: Advanced Technical Collaboration

Tier I activities were defined as scientifically-based technical exchanges that reflect the advanced capabilities of the partner country. The direct benefit of these interactions included increased US technical capability through sharing information on state-of-the-art analytical techniques, sharing sample characterization data and developing nuclear material databases, and increased international nuclear transparency.

The engagements within this area were mutually beneficial and involved activities such as the following:

- Analytical method sharing and best practices for nuclear forensic characterization of materials from across the fuel cycle: Many instrumentation and analytical methods have been well-developed by a number of our partner countries. The goal of this activity is to share advances in sample handling protocols, methods, and procedures developed specifically for the analysis of nuclear forensic samples.
- Development of sample protocol and quality assurance (QA)/quality control (QC) procedures for characterizing interdicted samples and other materials of forensic interest: This activity provided confidence-building to both parties through sample exchange and round-robin activities using techniques from the IAEA Nuclear Security Series #2 document to further analytical capability, ensure data intercomparability, and develop QA/QC procedures that could be shared with additional partner countries.
- Cooperative research and development to identify and validate signatures of nuclear materials from across the fuel cycle: Joint study of signatures specific to

a partner's fuel cycle processes and facilities (e.g., reprocessing method) are key to building an understanding of how to identify and assess the provenance of forensic samples of unknown origin.

- Cooperative research to develop tools for determining nuclear material provenance and comparisons between questioned samples and known signatures of nuclear and radiological materials: Computational tools are used for determining confidence in assessing the origin of nuclear materials (e.g., Bayesian models, multivariate statistical comparisons, reactor models).
- Scientific engagement to develop data architectures and search engines for nuclear forensic databases: Database activities were based on a US agreed-upon framework to share a data dictionary of the types of material characteristics with potential forensic value, seminars on implementation strategies, and data-sharing meetings when possible, noting there was never a requirement for partner countries to share potentially sensitive or proprietary information.

Tier II: Capacity Building and Transparency

Tier II activities involved capacity building and technical exchanges depending on the level of sophistication of the partner. The direct benefit of these interactions included sharing data and samples and developing nuclear material databases, identifying international partners and developing the relationships for analyzing interdicted materials, and promoting nuclear forensic best practices and increasing international nuclear security transparency. In some cases, activities listed under Tier I were appropriate, but additional capacity-building activities that fall under Tier II engagement included the following:

- Overview of cooperative research and development of analytical methods used for technical nuclear forensic examinations: This activity was aimed at partner countries new to making forensic measurements but with some experience with nuclear material characterization. Instrumentation and analytical methods such as those listed in IAEA Nuclear Security Series #2 were of varying familiarity to these partners, and raising awareness of the utility of these techniques was the goal of this activity.
- Bilateral sample and data exchanges to establish confidence in laboratory analysis capabilities and ensure intercomparability with other laboratories to support global nuclear forensics efforts: This activity promoted partner countries to develop and use techniques and methods to conduct analyses that the partner state has limited experience in using for nuclear forensic measurements and often included material analysis intercomparison exercise.
- Scientific engagement to encourage the adoption of a database structure to support a national nuclear forensic library: The implementation of US database architecture was necessary for capturing country-specific nuclear material information appropriate for countries that were not currently developing their own indigenous architecture.
- Engagement to promote nonproliferation best practices and understanding the relationship to nuclear forensics: This activity encouraged participation in GICNT, ITWG, and other confidence-building activities.

Tier III: Basic Material Handling, Characterization, Shipping, and Techniques for Ensuring Sample Integrity and Nuclear Forensic Best Practices

Tier III activities were capacity-building efforts to ensure that appropriate infrastructure and procedures existed to handle nuclear forensic samples and ensure data defensibility. The direct benefit of these interactions included strengthening international nuclear materials security, exchange of samples and/or data, promoting nuclear forensics best practices, developing basic response protocols for securing interdicted materials to maintain sample integrity, and sharing nondestructive/minimally destructive analysis techniques for nuclear material identification and assay. Example activities included the following:

- Promoted a basic understanding of nonproliferation nuclear forensics, including developing best practices for technical nuclear forensic activities: Seminars were held on the types of measurements necessary to implement a basic forensic characterization capability and where to find or how to develop the expertise, as well as nuclear materials handling courses (including some already developed for other audiences).
- Development and implementation of basic response protocols for securing interdicted materials, with a focus on chain of custody to ensure sample integrity: An interagency seminar on responsible parties was held and facilitated interaction between technical and law enforcement communities necessary for reliable nuclear forensic evidence examination.
- Sharing of nondestructive assay/minimally destructive analysis techniques for nuclear materials identification and assay for in-field identification, sample preservation, and health consequence management: These sharing sessions were based on courses already offered by the United States (mostly NNSA) that detailed protocols for the initial response when a material is found outside of regulatory control.
- Developed agreements to share information and materials from the front end of the nuclear fuel cycle (e.g., uranium ore and ore concentrates): This activity encouraged bilateral agreements to share materials and data.
- Developed procedures for shipping materials to appropriate facilities for forensic analysis and policies for the use of forensics data from an outside laboratory: This activity led to a training course on establishing security, chain of custody, and shipment of nuclear forensic evidence to an experienced laboratory, including considering country-specific rules of evidence that may now allow for data from outside of a country to be used as evidence in legal proceedings.

f. Expanding the Number of Partners

During this period of rapid expansion, INFC again leveraged the ministerial-level agreements in cooperative nuclear safeguards and security. Additional engagements with Australia, Brazil, Canada, South Africa, South Korea, and Taiwan were initiated under these blanket nuclear agreements, again framing the work under action sheets with specific deliverables. Another major engagement started during this era under the US–China Peaceful Uses of Nuclear Technology agreement with the Chinese Institute

of Atomic Energy. Using this developed framework, it was possible for INFC to focus on a few technical areas that forwarded the science of nuclear forensics. Specifically, additional investments in certified reference materials for radiochronometric age dating and exploiting trace elements in uranium ore concentrates for origin signatures were identified as of high importance to the international community; through the development of multiple action sheets, leveraging an international network of laboratories and SMEs was possible to make significant technical progress in these areas.

Another development was the initiation of the European Union's Chemical, Biological, Radiological, and Nuclear Centers of Excellence initiative, which sponsored a specific pilot project between the Association of Southeast Asian Nations countries and the Joint Research Center's Institute for Transuranium Elements. This project (number 30) was entitled "Network of Excellence for Nuclear Forensics in South East Asia Region" and involved a series of workshops to improve nuclear material identification and characterization capabilities across the region, the development of crime scene management protocols, and information on the development of a national nuclear forensics library. These workshops were developed in close coordination with INFC, and several INFC SMEs and HQ developed content for the workshops [17, 18].

3. Developed Stage (2013–2016)

a. 2014 and 2016 Nuclear Security Summits

By 2014, the Nuclear Security Summit process cemented nuclear forensics as a core capability within a comprehensive nuclear security regime with the Communiqué, specifically highlighting, "Nuclear forensics is developing into an effective tool for determining the origin of nuclear and other radioactive materials and providing evidence for the prosecution of acts of illicit trafficking and other malicious acts. We welcome the progress and recent development of several instruments that improve the use of traditional forensic methods, and emphasize the need to further develop innovative forensic methods and tools for investigating incidents involving nuclear and other radioactive materials" [5]. A new addition was a Joint Statement on Nuclear Forensics in National Security that identified several key commitments, including supporting "a knowledge platform to enhance the discussion and commitment amongst experts and policymakers; a survey of good practices to investigate nuclear security incidents; a nuclear forensics lexicon; [and] an education and training curriculum for experts, responders, and policymakers that deal with nuclear security incidents." The following countries signed on to the Joint Statement: Algeria, Australia, Canada, Chile, Czech Republic, Finland, France, Georgia, Hungary, Indonesia, Italy, Japan, Kazakhstan, Malaysia, Morocco, the Netherlands, Republic of Korea, Romania, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States of America [5].

The Japanese statement specifically called out bilateral work with the United States to develop technologies, methodologies, and resources dedicated to preventing the illicit trafficking of nuclear material. This bilateral work was one of the first partnerships the new DNN nuclear forensics program developed. The focus was on strengthening

material characterization techniques and in identifying additional distinguishing signatures. This work eventually grew into a discrete task under the US–Japan Nuclear Security Working Group [19].

b. Developing a Balance of Bilateral Engagements

The INFC program expanded rapidly in the 2010–2014 time frame, growing from a few partners to more than a dozen and developing engagement plans based with activities selected from the tier model described in the previous section. Specific program competencies were developed that allowed for a focus on science (Tier I), capacity building (Tier II), and training (Tiers II and III) and drew in a growing cadre of national laboratory SMEs to support each engagement. The result was a highly-successful series of bilateral projects with tangible results that included advancing the science of nuclear forensics, the implementation of best practices identified by the IAEA and ITWG, and increased global capacity for defensible nuclear forensics analysis, many of which were highlighted in national-level statements provided during the Nuclear Security Summits.

Focus on Science

One of the initial goals of INFC was to enhance US capabilities in nuclear forensics by partnering with nuclear experts in other countries. For most practitioners, nuclear forensics is simply another application of nuclear material characterization but with different end users of the data (law enforcement vs. regulatory bodies or fuel cycle process information). However, the fundamental laboratory techniques and instrumentation expertise required to make these measurements are the same. The result was that the first partnerships for INFC were with countries that already had advanced nuclear and radiochemistry laboratories. After SME elicitation and discussions with other US organizations involved in nuclear forensics, the first technical exchanges were those that supported advancements in the field of radiochronometry. This capability involves the measurement of radioactive materials and their decay products to determine a model age that reflects the time elapsed since purification (i.e., assumes a complete parent/progeny purification). Radiochronometry is a powerful material signature when trying to link a material to its possible origin and is useful in comparative and predictive evaluations. A comparative signature is when an unknown is compared with a known material to make interpretive inferences, whereas predictive signatures typically derive from underlying chemical or physical attributes related to a specific process that imparts the signature. Often, a predictive signature does not need an exact comparison to attribute the material to a specific process or timeline. Radiochronometry projects were undertaken as interlaboratory comparison exercises to ensure a consistent measurement baseline across multiple laboratories and eventually resulted in a number of publications [20–23] and the development and certification of a new ^{229}Th certified reference material critical for accurate uranium radiochronometry measurements [24, 25].

Focus on Capacity Building

In addition to the engagements that supported advancing the scientific discipline of nuclear forensics, INFC developed a series of engagements with partners who were

new to nuclear forensics and were repurposing or redirecting staff to apply their nuclear material characterization knowledge toward developing nuclear forensic laboratory capabilities. These engagements often involved the development and execution of procedures outlined in the IAEA's Nuclear Security Series #2 (and revised Nuclear Security Series #2-G) for initial categorization and characterization of nuclear and radioactive materials [26]. Several of these exchanges involved the characterization of uranium ores and the analyses of materials that would eventually serve as reference benchmarks for uranium analyses. In addition to developing and executing sample analysis plans, capacity-building exchanges provided visibility, often resulting in the further development of connections between law enforcement, regulatory, and technical agencies.

Focus on Training

It was clear from the beginning that for nuclear forensics to become fully integrated into the nuclear security lexicon, awareness and training would be required at all levels of government. The Nuclear Security Summit process ensured that the highest levels of government were engaged and committed; the GICNT focused on developing tools and practical exercises for policy makers; and the IAEA, ITWG, and INFC reached nuclear practitioners with a range of guidance documents, trainings, and other support to countries desiring to develop their nuclear forensics capabilities. INFC developed several training classes, including Introduction to the Model Action Plan, National Nuclear Forensics Libraries, [27] and specific primers on analytical techniques useful for forensic examinations such as alpha and gamma ray spectrometry, comprehensive destructive analysis, and inductively coupled plasma mass spectrometry.

Additional training and outreach opportunities expanded in the 2013–2016 time frame through partnerships with US DOS's Weapons of Mass Destruction Terrorism Office and their Counter Nuclear Smuggling unit (CNS). The CNS program unites offices across the United States to support outreach programs for the development of national-level counter nuclear smuggling policies and the coordination of US resources to support successful implementation. INFC was often called upon to support CNS outreach activities, which often led to bilateral engagement on technical topics with nuclear experts in those partner countries.

In addition to INFC developing additional training and exercise opportunities, we were also highly engaged with the IAEA as they continued to develop resources for member states implementing nuclear forensics capabilities. In the 2013–2016 time frame, INFC supported the revision of Nuclear Security Series #2, resulting in Nuclear Security Series #2-G, *Nuclear Forensics Support of Investigations* [26]; served on the coordinating committee and supported several presentations at the "Advances in Nuclear Forensics: Countering the Evolving Threat of Nuclear and Other Radioactive Material out of Regulatory Control" conference held in 2015 [28]; supported the drafting of technical document, "Application of Nuclear Forensics in Combating Illicit Trafficking of Nuclear and Other Radioactive Material" [29]; and provided key support for the 9-year effort to develop a technical document, "Development of a National Nuclear Forensics Library: A System for the Identification of Nuclear and Other Radioactive Material out of

Regulatory Control” (eventually published in 2018) [30]. INFC continued to serve as trainers and content providers for the IAEA Introduction to Nuclear Forensics and Nuclear Forensics Practitioners course.

4. Conclusions

The adoption of technical nuclear forensics and accompanying laws and legal investigations into nuclear and radiological materials out of regulatory control as a standard nuclear security practice took decades of work by hundreds of scientists and investigators, individual countries, and international organizations. These efforts have resulted in a more unified understanding of what measurements and practices need to be undertaken to ensure that perpetrators of nuclear smuggling are prosecuted and countries have a better understanding of what measurements are necessary to help support understanding vulnerabilities in their nuclear material control systems. The accounts in this paper detail the experiences with NNSA’s INFC, the IAEA, GICNT, and ITWG. Personally and professionally, it was an amazing time to be a part of bringing nuclear forensics to the forefront of policy and technical communities. The unique partnering of women across technical and policy domains, federal and laboratory settings, and throughout multiple federal agencies (NNSA, DOS, National Security Council, and Department of Homeland Security’s National Technical Nuclear Forensics Center) was unprecedented compared with many other US Government outreach efforts in nuclear security, safeguards, or safety. These women took ownership of the forensics domain and are a large part of the success over the years detailed in this article.

Though this paper highlights actions that occurred during the 2009–2015 time frame, efforts remain today through NNSA, the IAEA, and ITWG that continue to bring people together to help build capacity to understand and attribute the origins of materials found out of regulatory control.

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