NUCLEAR FORENSICS: FROM NATIONAL FOUNDATIONS TO GLOBAL IMPACT

SUMMARY OF A TECHNICAL MEETING

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2025

FOREWORD

Nuclear forensics supports national nuclear security measures and judicial proceedings by providing information on the identity, origin and history of nuclear or other radioactive material out of regulatory control. A nuclear forensic examination uses analytical techniques in the context of an investigation to obtain information about material of interest, or to collect evidence on material contaminated with radionuclides. A nuclear forensic capability can enhance national nuclear security programmes and support the enforcement of a nation's laws that prohibit the possession and use of nuclear or other radioactive material out of regulatory control.

IAEA Member States have been acknowledging and supporting the further development of nuclear forensics at the IAEA through General Conference resolutions dating from 2005 and thereafter. The IAEA programme of assistance in nuclear forensics has grown significantly over the past decade and includes training, coordinated research, technical advisory activities and published guidance. IAEA Nuclear Security Series No. 2-G (Rev. 1), *Nuclear Forensics in Support of Investigations*, provides guidance to States on implementing nuclear forensic capabilities, conducting nuclear forensic examinations and outlining the role of nuclear forensics in judicial proceedings and national nuclear security programmes.

This report provides technical information, such as details of analytical techniques and methodologies that are used in nuclear forensic examinations to support legal proceedings relating to nuclear security events. The report demonstrates that a significant outcome of the 2022 Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact was the improved integration and involvement of law enforcement personnel and prosecutors in the field of nuclear forensics.

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1. INTRODUCTION

1.1. BACKGROUND

Nuclear forensic science (hereafter ‘nuclear forensics’) is a subdiscipline of forensic science involving the examination of nuclear and other radioactive material, or of other evidence that is contaminated with radionuclides, in the context of legal proceedings. Nuclear forensics is a component of nuclear security and can support investigations of criminal or other intentional unauthorized acts involving nuclear or other radioactive material. Nuclear forensics, alongside other methods of investigation, can provide information that can assist investigators in enforcing laws and regulations that prohibit the possession and use of nuclear or other radioactive material out of regulatory control. Nuclear forensics can also help identify links between nuclear or other radioactive material out of regulatory control and people, places and incidents under investigation, as well as between disparate illicit activities involving nuclear or other radioactive material. Nuclear forensics can be used to assist in determining when, where and how the nuclear or other radioactive material was lost from regulatory control. It can also be used to support investigations and help authorities in the identification of deficiencies in nuclear material accounting and control systems, or vulnerabilities in physical protection systems at nuclear facilities and in radiation detection systems at borders, ports and other national points of exit or entry.

A State can perform a nuclear forensic examination as a component of a broader investigation — led by the State’s investigative authority — of circumstances and of possible criminal aspects in relation to the detection of nuclear or other radioactive material out of regulatory control. In a nuclear forensic examination, nuclear or other radioactive material is analysed using scientific instruments and analytical techniques capable of measuring the physical, chemical, elemental or isotopic properties of the material. A nuclear forensic examination results in the generation of technical data that, once interpreted, can support the needs and obligations of the investigative authority. A nuclear forensic examination can make use of one or several analytical techniques to examine the material, resulting in the generation of data that can be used in the investigation. While instruments and analytical techniques are an inherent aspect of the nuclear forensic analysis, subject matter experts with experience using these instruments will also be needed by the State to perform these analyses. In addition, subject matter expertise is essential in the interpretation and reporting of nuclear forensic data to support the investigative authority’s needs in relation to the circumstances of the incident. As part of a nuclear forensic examination, specific procedures can be applied to analyse other evidence contaminated with radionuclides in a safe and comprehensive manner, potentially providing the investigative authority with information that is complementary to findings about nuclear or other radioactive material.

The science of nuclear forensics has developed greatly since its inception in the early 1990s. Over the last thirty years, States have made considerable progress in the development and implementation of nuclear forensics, often prompted by national legislation. Many States have recognized the value of communicating their developments in nuclear forensics to a wider audience. The IAEA, for its part, provides diverse forums for States to present or publish scientific results or methodological developments in nuclear forensics, for example at international conferences or technical meetings, and in technical reports or publications.

1.2. OBJECTIVE

The technical meeting was organized in line with recent IAEA resolutions from the General Conference that support further development of nuclear forensics among Member States, as well as to incorporate the outcomes from the IAEA International Conference on Nuclear Security: Sustaining and Strengthening Efforts, which took place in Vienna on 10–14 February 2020 (ICONS 2020).[1] The technical meeting also fulfilled a key task outlined in Section 58 of the IAEA Nuclear Security Plan 2022–2025: "Sharing experiences, lessons learned and good practices in radiological crime scene management and nuclear forensics science through technical meetings and workshops" [1]. Objectives of the technical meeting included a focus on the application of nuclear forensics in response to incidents involving nuclear and other radioactive material out of regulatory control, as well as links to radiological crime scene management and support for potential judicial proceedings. The technical meeting also served as an opportunity to highlight States' experiences in using nuclear forensics for the prevention of, and response to, criminal or other intentional unauthorized acts involving nuclear or other radioactive material out of regulatory control.

The meeting was organized around four topical areas:

(1) Nuclear forensics capability building;
(2) Nuclear forensics as a national responsibility;
(3) Nuclear forensics sustainability and cooperation;
(4) Nuclear forensics and radiological crime scene management, and their intertwined nature.

Presentation abstracts were solicited for these topical areas and select sub-themes. In advance of the meeting, presenters wrote and submitted abstracts to the IAEA for review and approval.[2] Meeting organizers selected and grouped presentations into eight technical sessions and four poster presentation sessions, described in Chapter 2 of this report. The concluding portion of this report will address ways in which the technical meeting sessions supported and addressed the key themes.

1.3. SCOPE

This report is a summary of the presentations and sessions of the 2022 Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact, which took place in Vienna on 11–14 April 2022. The report is intended for an audience of technical and non-technical stakeholders responsible for developing and implementing nuclear forensic analytical capabilities within the context of broader national nuclear forensic programmes stemming from national legislation. This report does not provide specific guidance on procedures for nuclear forensic science; rather, it provides information on ongoing research projects, exercises, activities and trends in nuclear forensics and radiological crime scene management as of April 2022. It summarizes conversations that occurred in panel discussions featuring experts in nuclear forensics and associated areas, and describes several interactive exercises and demonstrations that occurred at the meeting.

1.4. STRUCTURE

Section 2 of this report summarizes all of the sessions and presentations delivered during the four day technical meeting. Section 3 reviews the meeting's key themes and offers some conclusions on the effectiveness of the meeting at addressing these themes. The appendix includes information on the Steering Committee and the Secretariat of the 2022 Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact.

2. SUMMARY OF THE MEETING SESSIONS

The 2022 Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact comprised an opening session, five keynote presentations, nine panel discussions, eight technical sessions, four poster

[1] For more information on ICONS 2020, see: www.iaea.org/events/nuclear-security-conference-2020

[2] The Book of Abstracts for the 2022 Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact is available at: https://conferences.iaea.org/event/266/

presentation sessions, interactive content sessions, side events, mini exercises and a closing session. In addition, the meeting included a number of case studies, a nuclear forensics drama theatre (i.e. a mock trial), and a session and mini exercise dedicated to the 25th anniversary of the Nuclear Forensics International Technical Working Group.

2.1. OPENING SESSION

Ms. Elena Buglova (IAEA), on behalf of the Division of Nuclear Security in the Department of Nuclear Safety and Security, opened the 2022 Technical Meeting on Nuclear Forensics by welcoming all of the participants. She emphasized that the division had been making continuous efforts throughout the COVID-19 pandemic to meet its obligations to IAEA Member States, largely through virtual means, and she expressed her gratitude to see so many attendees in person at one of the first hybrid technical meetings held in Vienna since March 2020.

Ms. Buglova stated that nuclear security is a national responsibility and that national authorities hold the primary duty for ensuring that nuclear and other radioactive material, associated facilities and related activities are sufficiently secured within State borders. The IAEA has emerged as a recognized global actor with a central role in coordinating nuclear security efforts globally and in providing assistance to States for the establishment or maintenance of robust nuclear security regimes.

Ms. Buglova underlined the important role of nuclear forensics in any States' nuclear security architecture: enabling the investigation of criminal or other intentional unauthorized acts by effectively tracing the source, identity and process history of radioactive material. Together with radiological crime scene management, nuclear forensics provides not only a response to illicit activities involving nuclear and other radioactive material but also functions as a deterrent that can help prevent or further discourage such acts. She continued to elaborate on the IAEA commitment, as stated in the Nuclear Security Plan for 2022–2025, to position nuclear forensics as one of the key components of an effective nuclear security regime.

In recent years, she continued, the IAEA has seen a continuous increase in requests from its States seeking to strengthen their national capacities in the area of nuclear forensics and radiological crime scene management. The IAEA provides support for nuclear forensics (e.g. technical assistance, training, research programmes, development of national nuclear forensics libraries) to support States that wish to acquire and maintain the resources and skills needed to meet demands in this area.[3] In 2021, as a result of COVID-19, these efforts were mainly delivered through virtual means, including through webinars, virtual meetings and distance learning. The IAEA also launched a new nuclear forensics e-learning module in 2021, providing participants with an overview and basic introduction to nuclear forensics.[4]

Ms. Buglova used the opportunity to draw attention to capacity building efforts, making specific reference to the new IAEA Nuclear Security Training and Demonstration Centre (NSTDC), a flagship nuclear security centre under construction at the IAEA Seibersdorf Laboratories near Vienna. Estimates indicate that construction of the centre will be complete by the end of 2023, with the centre housing a dedicated area for nuclear forensics and radiological crime scene management.

Finally, Ms. Buglova outlined the objectives of this technical meeting, organized by the IAEA Division of Nuclear Security: to focus on the application of nuclear forensic science in response to incidents involving nuclear and other radioactive material out of regulatory control, and on the demonstration of links to radiological crime scene management, as well as on support to potential judicial proceedings. The agenda is

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[3] For more information on IAEA assistance in nuclear forensics, see www.iaea.org/topics/nuclear-forensics

[4] For information on Nuclear Security eLearning at the IAEA, see www.iaea.org/topics/security-of-nuclear-and-other-radioactive-material/nuclear-security-e-learning

aligned with recent IAEA General Conference Resolutions on nuclear security and the outcomes of ICONS 2020. Ms. Buglova stressed the importance of holding such meetings, which provide an opportunity for nuclear and forensic scientists, nuclear security event responders, law enforcement officials; prosecutors, nuclear regulators, nuclear security specialists and many others to exchange information and knowledge. She concluded her remarks by thanking everyone for their participation and wishing all of the participants a fruitful technical meeting.

Ms. Ruth Kips (USA), co-chair of the 2022 Technical Meeting on Nuclear Forensics, welcomed the participants to Vienna and thanked everyone for their participation in the technical meeting. Ms. Kips, from Lawrence Livermore National Laboratory (LLNL), emphasized the challenges that arose as a result of COVID-19, but she also shared ways in which pandemic-driven problem solving has strengthened the international nuclear forensic community over the preceding two years. Ms. Kips stated that the 2022 technical meeting's theme, 'From National Foundations to Global Impact', complemented the key themes of the technical meeting in 2019, which focused on the sharing of good practices, the role of nuclear forensic science in responding to events involving the detection of nuclear or other radioactive material outside of regulatory control, and the benefits of regional and international cooperation on nuclear forensics.

Mr. John Buchanan (The International Criminal Police Organization, Interpol), Coordinator of the International Criminal Police Organization's Radiological and Nuclear Terrorism Prevention Unit (RNTPU) and co-chair of the 2022 Technical Meeting on Nuclear Forensics, opened his remarks by thanking the organizers for the invitation to the meeting. He explained that terrorism and organized crime are high priority areas for Interpol, and particularly within the RNTPU, which is working to promote information sharing and capacity building in States for the prevention, detection and investigation of, as well as the response to, radiological and nuclear terrorism. In the context of the technical meeting, Mr. Buchanan underscored the importance of investigations in response to events involving the detection of nuclear or other radioactive material out of regulatory control. The aim of Interpol is to investigate and prosecute those involved in such activities. Law enforcement officers depend on technical support from the scientific community and international organizations, such as the IAEA, for such work, and these objectives can only be achieved through cooperation and collaboration. In the last decade, Mr. Buchanan indicated that nuclear forensics had evolved from having a pure scientific and technical focus to more broadly include support for the investigation of nuclear security events. He concluded his remarks by emphasizing the need to bridge nuclear forensic science with law enforcement activities.

Following the opening remarks from Ms. Buglova, Ms. Kips and Mr. Buchanan, **Ms. Éva Széles** (IAEA) welcomed all of the participants and provided an overview of the IAEA Crime Scene Management and Nuclear Forensics Unit's aim to implement activities concerning the development of radiological crime scene management and nuclear forensic capabilities for States. Ms. Széles described the assistance that the Agency offers to strengthen global nuclear forensic work, for example through training courses and through the IAEA Residential Assignment Programme for Nuclear Forensics, which offers an opportunity to early career scientists or nuclear forensic practitioners to be hosted by advanced nuclear forensic laboratories that provide hands-on training and help develop skills. Ms. Széles elaborated on additional activities organized and carried out by the IAEA, including expert missions on behalf of the Agency, technical visits, technical meetings and coordinated research projects, during which participating States share experiences and recent research developments in nuclear forensic science. She also noted that nuclear forensics is a discipline that is informed by policy, effectuated by law enforcement and implemented through science. A key focal point for the Agency is to further strengthen the critical relationship between radiological crime scene management and nuclear forensics, as the former needs strong scientific support to ensure the highest level of confidence in the investigation. Confidence in the management of a radiological crime scene is also essential for all aspects of nuclear forensic investigations, from in-field categorization and sample collection to safe and secure transport. Ms. Széles described the development of virtual programming for radiological crime scene management and nuclear forensics during the COVID-19 pandemic. This virtual programming included a seminar series, an eLearning module, discussion-based exercises, consultancy meetings, workshops and seminars, all of which were held virtually.

Ms. Széles listed some of the objectives of the technical meeting: to discuss the application of nuclear forensics in response to incidents involving nuclear and other radioactive material out of regulatory control; demonstrate links between nuclear forensics and radiological crime scene management; offer support to potential judicial proceedings; and highlight States' experiences in using nuclear forensics for the prevention of, and response to, criminal or other intentional unauthorized acts involving nuclear or other radioactive material out of regulatory control. Ms. Széles communicated the importance of nuclear forensics in support of investigations, and provided details on the 'from crime scene to courtroom' model, the subject of a panel discussion that she would later oversee with the support of partner international organizations. She noted the IAEA's focus on human resource development through the creation of more interactive training material, new courses and cross discipline training, as well as through use of the new IAEA Nuclear Security Training and Demonstration Centre (NSTDC) in Seibersdorf. Ms. Széles concluded her remarks by reiterating the need for a strong link between radiological crime scene management and nuclear forensics, and the need for both topics to be integrated into national legal systems and nuclear security response frameworks.

2.2. KEYNOTE PRESENTATIONS

Throughout the technical meeting, Keynote addresses were delivered by a professionally and geographically diverse set of experts, whose remarks helped to situate the field of nuclear forensics in the context of global nuclear security.

2.2.1. Keynote address 1

Mr. Simon Minks (Netherlands) provided the first Keynote address, with **Mr. Kevin O'Prey** (USA) as the moderator. Mr. Minks, from the Netherlands Ministry of Justice and Security, dedicated the opening portion of his keynote remarks to the relationship between nuclear forensic experts and the courtroom. He emphasized the importance of communication, stating that if the parties involved in a nuclear forensic investigation and prosecution do not speak the same language in the courtroom, the prosecutors cannot achieve their goals. As such, Mr. Minks encouraged anyone involved in these processes (e.g. nuclear forensic scientists, prosecutors, defence lawyers) to make their expectations clear and ask questions, even if the questions seem simple.

In response to the moderator's query on what has worked well in the courtroom, both in the case of evidence and data types, as well as in the case of communicating complex concepts, Mr. Minks reiterated the indispensability of effective communication. If the prosecution cannot understand the work of the experts, the case will not be successful. In addition, the prosecution will want to demonstrate the value of a nuclear forensic science expert by asking, "Why are you an expert?" and "Is this work state of the art or not?" Mr. Minks also explained that during cross-examination, it is critical for experts to remain clear and impartial. Nuclear forensic science experts can practice skills in relation to the courtroom during training courses. He also advised experts to prepare themselves in advance for potential questions by clarifying the points that they would like to make during the court case.

When asked his opinion on the importance of technical details to the overall criminal investigation, Mr. Minks explained that technical details are one of a number of important aspects of legal proceedings, together with criminal intent, the background of the suspect and the chain of custody. Furthermore, he noted that in an international legal case, differences in the methodologies of countries could arise, and the relevant parties will want to be informed of best practices and the state of the art. One of the key points of Mr. Minks' presentation concerned communication: from the very beginning, "talk with the investigator, talk with each other". He urged involved parties to clearly communicate their expectations for the findings and to stay independent.

Mr. O’Prey then asked Mr. Minks to discuss how expertise can be challenged in a courtroom. One strategy of the prosecution, he explained, could be to interrogate the expert and challenge his or her credentials. Experts could be asked about past mistakes or inconsistencies. For example, an expert’s testimony in a prior case might have been invalidated because he or she employed incorrect or outdated methods. As such, experts’ credentials have to be verified, and they need to have a strong background, along with training in cross-examination. Mr. Minks also noted the likelihood that cases will be appealed, which would necessitate repeated testimony and additional time and effort on the part of the expert.

When asked how the legal system might stay up to date on nuclear forensic technical developments, Mr. Minks responded that in the absence of any formal means for prosecutors to stay up to date, they rely on the expertise of experts, and they will expect that the analytical methods employed follow international norms. If the expert can convince the prosecutor that methods are state of the art and employed skilfully, the prosecutor can then convince the jury on this basis.

The keynote session concluded with questions from the audience. In response to a question on whether well established, traditional forensic methods or newly developed methods in nuclear forensics are ‘better’, Mr. Minks said that it is the responsibility of the technical team and experts to convince the legal team that one method is better than another. Another question concerned the appeal process and whether testimony could be changed during the appeal. Mr. Minks responded that it will depend on the party that is employing the expert and if a different set of questions will be asked. The keynote address concluded with Mr. Minks reiterating that establishing effective communication between the prosecutors and the scientists, co-organizing training and developing skills in both areas (i.e. legal and technical) are the keys to success.

2.2.2. Keynote address 2

The keynote address from **Mr. Jay Tilden** (USA) was in the form of a question and answer session, with **Mr. Kevin O’Prey** (USA) as the moderator. The opening question pertained to the position of nuclear forensics as a component of nuclear security: how does the ability to identify the origin of material assist nuclear security, and what happens if these capabilities deteriorate? Mr. Tilden welcomed the opportunity to speak to the audience and first clarified the role of his organization, the National Nuclear Security Administration, which is responsible for enhancing national security through the application of nuclear science, supporting the FBI and intelligence community, bringing technical expertise to forensics, facilitating nuclear preparedness and ensuring a response to a nuclear or other radiological security event. In Mr. Tilden’s view, the goal is not only to prevent these capabilities from diminishing, but also to sustain and strengthen them. He acknowledged that all of the countries in attendance at the technical meeting recognize the importance of instituting strong nuclear security mechanisms. Mr. Tilden highlighted the recurring conclusion from various relevant meetings, reviews and summits: *nuclear forensics is a key component of the global nuclear security architecture*. He continued by enumerating the benefits of strong nuclear security, such as taking full advantage of the carbon free nuclear energy infrastructure, maintaining the ability to interdict and investigate smuggling and trafficking, and supporting deterrence through investigations and prosecutions.

Mr. O’Prey then shifted the discussion to the topic of deterrence, and more specifically to the relationship between nuclear forensics and deterrence, as well as the challenge of deterring non-state actors. From a historical perspective, Mr. Tilden indicated that countries with nuclear weapons capabilities have an incentive to understand the signatures of their own material. Before being banned, nuclear testing contributed significantly to nuclear forensic capabilities around the world. In the 1990s, the nuclear forensic community was faced with the need to retain capabilities despite the lack of nuclear weapons testing. In recent decades, the rise of non-State actors and nuclear security threats have enhanced the importance of nuclear forensics and deterrence. Mr. Tilden noted that deterrence by denial is the first line of defence; as such, nuclear security is critical because it ensures that nuclear or other radioactive material does not reach a non-State actor intent on committing a criminal or other intentional or unauthorized act. Export controls are also important to prevent non-State actors from procuring the non-nuclear material needed to undertake a destructive attack. Mr. Tilden noted that the availability of expertise and information through the publication or spread of sensitive information (e.g. online) is difficult to prevent, particularly once it has already been distributed, and thus the importance of deterrence by denial. Finally, Mr. Tilden noted that the credible attribution of nuclear material to States compels them to behave responsibly and transparently.

In response to an audience question, Mr. Tilden spoke about the use of other radioactive material and the roles of State and non-State actors. He noted that the global intelligence community has observed that the number of dirty bomb incidents is lower than anticipated. Mr. Tilden also indicated that harm from the detonation of a radiological dispersal device stems more from explosive material than from radioactive material, but that the fear of radiation was nonetheless a major psychological factor.

Mr. O'Prey prompted Mr. Tilden to discuss his recently published, co-authored article on nuclear forensics and deterrence, entitled The Evolving Missions of Technical Nuclear Forensics [2]. The paper centres on the consequences that could be associated with a lack of transparency in relation to a major nuclear incident or accidental nuclear detonation, which could spiral into a major international incident or crisis. Mr. Tilden explained that in such cases, nuclear forensics can help make determinations about the nature of the incident, thereby reducing the chances that a State can deny involvement in the incident, and providing an opportunity to establish measures for prevention of future incidents, both accidental and intentional.

An audience member asked Mr. Tilden to address: (1) the extent to which nuclear forensic science can help build capabilities in nuclear safety and security; and (2) the kinds of deterrence measure that can be taken, particularly in relation to the non-proliferation of nuclear weapons and technology. Mr. Tilden responded that nuclear safety is paramount, and that it is possible to model and estimate the likelihood of an accident. Following closely behind nuclear safety is nuclear security and the safe use of nuclear material. Nuclear forensics, he continued, comes into play later, in the case that material falls outside of regulatory control. The USA sees nuclear forensics as a day to day practice, investing significant spending to understand the signatures of nuclear and other radioactive material out of regulatory control. Mr. Tilden reminded the audience that early reports of an incident are often inaccurate and that robust techniques (e.g. nuclear forensic techniques) can be employed to answer difficult questions.

2.2.3. Keynote address 3

Mr. Klaus Mayer (European Commission) began his keynote remarks by noting that the Joint Research Centre in Karlsruhe, Germany (JRC-Karlsruhe) is the key scientific organ of the European Commission. He indicated that the purpose of JRC-Karlsruhe is to develop scientific solutions to policy issues established by the European Commission. Because the European Commission has identified nuclear security as a priority area, it follows that JRC-Karlsruhe plays a central role in the development of technical solutions to nuclear security issues.

Mr. Mayer described the importance of the EURATOM treaty as the key legal basis of many activities at JRC-Karlsruhe. He listed the three major areas of nuclear security research at JRC-Karlsruhe, as follows: (1) nuclear science applications; (2) nuclear safety and waste management; and (3) nuclear safeguards, non-proliferation and nuclear security. The objectives and activities of JRC-Karlsruhe include research and development (R&D) (e.g. nuclear forensic signatures and new analytical methods), activities concerning capacity building (e.g. training at the European Nuclear Security Training Centre (EUSECTRA) and support of European Union Chemical, Biological, Radiological and Nuclear (CBRN) Risk Mitigation Centres of Excellence) and cooperative activities with international organizations and participation in joint exercises in nuclear forensics.

Mr. Mayer provided some details on nuclear forensic R&D that JRC-Karlsruhe has been focusing on in recent years, including research in microanalytical techniques, and elemental and isotopic mapping of nuclear forensic samples using laser ablation inductively coupled plasma mass spectrometry (ICP-MS). The use of radiochronometry (i.e. 'age dating') techniques has also been a major research focus, particularly in the development of new plutonium certified reference material, with certified production dates. Additional research has focused on the use of textural analysis from scanning electron microscopy (SEM) of uranium ore concentrate material, as well as the use of hyperspectral techniques to examine small differences in colour.

Furthermore, Mr. Mayer highlighted the essential role that 'traditional' forensics plays during the examination of nuclear or other radioactive material out of regulatory control. JRC-Karlsruhe has taken particular interest in the examination of traditional evidence contaminated with radionuclides. One study, for example, focused on a 'dirty bomb' scenario, in which the dispersion of $^{137}CsCl$ and $^{90}SrTiO_3$ was assessed after controlled chemical explosives tests. Data evaluation is ongoing.

In the area of capacity building in nuclear forensics, Mr. Mayer described three priority areas for JRC-Karlsruhe: (1) national nuclear forensic libraries (NNFLs); (2) training and technical exercises to maintain State nuclear forensic capabilities; and (3) training the next generation of nuclear forensic scientists around the world. As examples of nuclear forensic training efforts, Mr. Mayer cited field and tabletop exercises, including a green border scenario conducted by Moldova, a national level scenario conducted in Ukraine, and a point of entry scenario conducted in Georgia. Since these exercises were conducted during the COVID-19 pandemic, Mr. Mayer noted that the experience for participants was markedly different from in-person exercises. He also described internships supported by JRC-Karlsruhe and held in Ukraine, as well as the development of a nuclear forensics summer school programme, which hosted 21 young scientists from Georgia, Ukraine, Azerbaijan and Moldova.

Mr. Mayer concluded with an assessment of the role of JRC-Karlsruhe moving forward, noting that activities in nuclear security would experience a budget cut, affecting the period of 2021–2027. In spite of this challenge, he underlined that "a bend in the road is not the end of the road, unless you fail to make the turn." JRC-Karlsruhe plans to continue activities in the area of nuclear forensics, and will remain a key player in the international community of nuclear forensic practitioners.

2.2.4. Keynote address 4

Mr. Mikhail Kondratenkov (Russian Federation), from the Ministry of Foreign Affairs, began his remarks by welcoming the participants and acknowledging the efforts of the IAEA Secretariat in organizing the meeting. He noted the importance of nuclear forensics in the prevention of nuclear terrorism, nuclear smuggling and trafficking. Because incidents involving nuclear or other radioactive material have potential societal impacts, it is critical that governments work to combat nuclear security threats. Nuclear forensics remains a key response mechanism to combat nuclear and other radioactive material out of regulatory control, and to prevent control from being lost over such material. Mr. Kondratenkov recognized the efforts of the Nuclear Forensics International Technical Working Group (ITWG)[5] in expanding nuclear forensics throughout the world, noting its increased membership and the growing number of activities. He also emphasized the role of the Global Initiative to Combat Nuclear Terrorism (GICNT), which has played a key part in nuclear

[5] The Nuclear Forensics International Technical Working Group, founded in 1995, is an informal association of official nuclear forensics practitioners that is open to all States interested in nuclear forensics. The ITWG's objective is to advance the scientific discipline of nuclear forensics (i.e. techniques and methods for forensic analysis of nuclear and other radioactive material, and radiologically contaminated material) and to provide a common approach and effective technical solutions to competent national or international authorities that request assistance. For more information, see: www.nf-itwg.org

forensics since its inception. Finally, he acknowledged the efforts of the IAEA, highlighting more specifically the conferences and technical meetings that have been held on nuclear forensics.

In addition, Mr. Kondratenkov described the role of the Russian Federation in the development of nuclear forensics, noting technical developments that have proven to be informative in determining the nature of nuclear and other radioactive material out of regulatory control. He emphasized in particular the importance of establishing the origin of nuclear or other radioactive material out of regulatory control, in addition to the importance of using nuclear forensic data in legal proceedings. Nuclear forensics can provide great insight into the origin, proliferation pathway, and suspected use of nuclear and other radioactive material, as well as some indication of criminal or other intentional unauthorized acts. Finally, he concluded by elaborating on some areas for future development that the Russian Federation would be pursuing in nuclear forensics.

2.2.5. Keynote address 5

The keynote remarks from **Mr. John Buchanan** (Interpol) were in the form of a fireside chat with **Mr. Kevin O'Prey** (USA) as the moderator. When asked to reflect on the principal successes of law enforcement against the smuggling and trafficking of nuclear and other radioactive material, Mr. Buchanan first remarked that success has been experienced in terms of prosecution and conviction in individual cases against smugglers and traffickers of nuclear and other radioactive material. Beyond that, he emphasized that law enforcement successes include developing direct links and reaping the indirect benefits from efforts to combat the smuggling and trafficking of nuclear and other radioactive material. In the past five years, in particular, emphasis has been placed on raising awareness among law enforcement officials concerning the risks posed by terrorist groups and organized crime in relation to nuclear and other radioactive material. Polling results from the interactive presentation software used during the meeting indicate greater representation (i.e. by a factor of two) from law enforcement than was seen approximately five years ago. Mr. Buchanan acknowledged that it is an improvement and demonstrates an increased awareness among the law enforcement community.

The discussion then shifted to progress in the legal framework at the national level and the science of nuclear forensics. Mr. Buchanan related his experience of learning new and exciting scientific developments each time that he attends meetings such as the IAEA technical meeting, but emphasized that subsequent communication regarding these developments and the sharing of information remain areas in need of significant improvement. He also noted that many national response plans remain in draft form, yet to be signed by the competent authorities, and are therefore outside of national legal frameworks at present.

Mr. Buchanan encouraged IAEA Member State personnel who want to champion nuclear forensics in their own countries to pursue the Integrated Nuclear Security Support Plan (INSSP), bringing stakeholders together to identify gaps and build capacity through multi-year engagement and commitment. Mr. Buchanan also mentioned ways in which Interpol can assist, including through programme assessment and long term support. He encouraged the use of tools, such as the GICNT self-assessment, to understand not only one's own responsibilities, but also where there are gaps in capabilities. Stakeholders participating in such programmes aim to collaborate — and not to compete with each other — while acknowledging the challenges associated with bureaucratic hurdles.

When prompted about trends that most concern him in the smuggling and trafficking of nuclear and other radioactive material, Mr. Buchanan stated that theft remains an important issue and that more could be done to understand intent. He also explained that scams are increasing, yielding concern about prospective buyers, their motivations and the market in which potential buyers operate. Mr. Buchanan also noted a concerning decrease in reporting, for example to the IAEA Incident and Trafficking Database (ITDB) as the timely reporting of incidents is key to success in this area. Finally, Mr. Buchanan noted the importance of establishing and formalizing a national response plan in States that do not presently have one, or where the plan remains in its draft form.

When asked by a conference attendee for advice on developing national response plans, Mr. Buchanan acknowledged that developing such a plan is a considerable undertaking that is difficult to assemble, but he suggests beginning with the formation of multi-agency working groups to bring stakeholders together and build relationships, while also considering engagement at the ministerial level, since high level government backing is likely to facilitate the development of an effective national response plan by motivating all of the stakeholders involved. In response to a question regarding nuclear material and environmental crimes, Mr. Buchanan agreed that including all of the relevant parties and working collaboratively will help avoid key omissions from a national response plan.

2.2.6. Key themes emerging from the keynote presentations

The invited keynote presentations situated the field of nuclear forensics in the global nuclear security context. Mr. Minks emphasized that the parties involved in a nuclear forensic investigation and prosecution have to clearly communicate in order for the prosecutors to achieve their goals in the courtroom, while Mr. Tilden described the relationship of nuclear forensics to deterrence, as well as the role of export controls in preventing non-State actors from procuring the material needed to perform an attack. Mr. Mayer focused his remarks on the role that institutions conducting nuclear forensics can play in support of multinational treaties. He also emphasized the importance of capacity building in nuclear forensics through field and tabletop exercises, as well as the development of future generations of experts through internships, engagement and mentorship. Mr. Kondratenkov's remarks stressed the importance of cooperating in nuclear forensics at the international level and of the prevention of nuclear terrorism through the combat against nuclear smuggling and trafficking. Mr. Buchanan noted achievements and areas for improvement in aligning law enforcement with nuclear forensic programmes, and he also underlined the importance of improving communication and information sharing between competent parties and stakeholders. A unifying theme that emerged from the keynote speakers' interventions is that the technical and scientific rigour of nuclear forensic science, in parallel with its effective application to investigations, prosecutions, deterrence and prevention, makes nuclear forensics a key component of the global nuclear security architecture.

2.3. PANEL DISCUSSIONS

Panel discussions throughout the technical meeting were organized by theme and allowed for multiple voices within the nuclear forensic science community to be heard in interactive conversations.

2.3.1. Keynote panel — Nuclear forensics within a nuclear security framework

A panel discussion was convened on considerations made by States when developing a nuclear forensic capability within a nuclear security framework. The panel consisted of Ms. Tegan Bull (Australia), Mr. Michael Curry (USA) and Ms. Anita Nilsson (Sweden), with Mr. O'Prey (USA) acting as the moderator.

Ms. Bull explained that, despite their many similarities, nuclear forensics and nuclear safeguards sometimes are overseen by separate entities within a State. She noted that cross-cutting activities between nuclear forensics and nuclear safeguards are beneficial in ensuring that collaboration can occur at the national, regional and international levels. In response to a question about efforts to ensure that nuclear security remains a priority for States, Ms. Bull reminded participants that the Joint Statement on Forensics in Nuclear Security INFCIRC/917 [3] was drafted by the Permanent Mission of Australia and endorsed by 30 States. She highlighted that the document could be used to justify the expenditure of resources on the development of nuclear forensics, and she invited interested non-signatory States to request that their signatures be added to the statement. Finally, she concluded that goals and objectives had been achieved in nuclear forensics through joint efforts, and that such achievements would not be possible with only a single team or organization. Because the journey towards a functioning nuclear forensic capability can be a great undertaking for some States, she highlighted the importance of taking small, successive steps towards achieving this aim. Many States can benefit from a gradual approach to the development of nuclear forensics.

Mr. Curry highlighted the role that the ITWG plays in encouraging international collaboration in nuclear forensics and radiological crime scene management. He noted that because nuclear forensic scientists and law enforcement investigators sometimes have a different approach to the problem of nuclear and other radioactive material out of regulatory control, more work needs to be done to bridge this gap. He also described the challenges of working within a national framework, and particularly the State mission to prevent all acts of terrorism involving nuclear and other radioactive material. Because incidents involving the smuggling or trafficking of nuclear or other radioactive material are detected infrequently in many States, it can be difficult to measure and demonstrate the success of individual States in this regard. He noted that the USA is continually updating policies and procedures on nuclear security, taking a 'whole of government' approach. He described the importance of demonstrating how the science of nuclear forensics can be used to support investigators and prosecutors, advising States to identify specific needs that could be elevated to policymakers who might offer their support.

Ms. Nilsson outlined developments in nuclear forensics since the 2014 International Conference on Advances in Nuclear Forensics: Countering the Evolving Threat of Nuclear and Other Radioactive Material out of Regulatory Control. She noted in particular the technical developments in analytical techniques, including the use of micro-analytical techniques to characterize nuclear and other radioactive material out of regulatory control. She described how the nuclear forensics and nuclear safeguards communities have learned from each other, noting the importance of cross-cutting approaches to nuclear security. She also described the importance of communicating the successes of nuclear forensics to policymakers and to the general public, further noting that both existing technologies and new approaches that will lead to additional successful investigations.

2.3.2. Panel discussion 1 — Legal framework and the Convention on the Physical Protection of Nuclear Material (CPPNM) and its Amendment (CPPNM/A)

A panel was convened to discuss the legal framework for nuclear security and the Amendment to the Convention on the Physical Protection of Nuclear Material [4] (A/CPPNM), as well as the role that radiological crime scene management and nuclear forensics play in the obligations of States Parties under the CPPNM [5] and its Amendment. The panel was moderated by Mr. Kevin O'Prey (USA), and included Mr. Frank Wong (USA), Mr. Jonathan Herbach (IAEA), Ms. Anita Nilsson (Sweden) and Ms. Maia Silagadze (Georgia). This panel discussion used an interactive presentation software to undertake anonymous polling in an effort to engage the audience.

Mr. Wong provided a brief introduction to the A/CPPNM, explaining that States Parties have to ratify the Convention (CPPNM) and its amendment (A/CPPNM) separately. The A/CPPNM, which was drafted in 2005 and entered into force in 2016, does not explicitly mention radiological crime scene management or nuclear forensics. However, radiological crime scene management and nuclear forensic science can assist States Parties in meeting their obligations under the A/CPPNM. For example, Article 5 of the A/CPPNM states:

"In the case of theft, robbery or any other unlawful taking of nuclear material or credible threat thereof, States Parties shall, in accordance with their national law, provide co-operation and assistance to the maximum feasible extent in the recovery and protection of such material to any State that so requests" [4].

Furthermore, Article 13 of the A/CPPNM states:

“States Parties shall afford one another the greatest measure of assistance in connection with criminal proceedings brought in respect of the offences set forth in article 7, including the supply of evidence at their disposal necessary for the proceedings. The law of the State requested shall apply in all cases” [4].

Mr. Herbach also provided introductory remarks, clarifying that not all States Parties to the A/CPPNM are IAEA Member States and not all IAEA Member States are parties to the A/CPPNM. The A/CPPNM is open to all States and to certain regional organizations (e.g. EURATOM). Mr. Herbach outlined the pillars of the Convention, which are the physical protection of nuclear material for peaceful purposes during international transport, the criminalization of certain offences involving nuclear material and international cooperation. He referred interested parties to Article 7 of the A/CPPNM for further details on the expansion of these pillars in the Amendment to the Convention [4].

Through the use of polling, the panellists were able to provide insight into audience responses on the fundamental principles of physical protection that are perceived to be closest to nuclear forensics. The most popular responses were: the responsibility of the State, the legislative and regulatory framework, nuclear security threats and the security culture. **Ms. Nilsson** noted that the Conference of the Parties to the Amendment to the Convention on the Physical Protection of Nuclear Material (A/CPPNM) 2022 occurred about one week before the technical meeting, and she emphasized that, because of the international network and expertise created thanks to the A/CPPNM, the A/CPPNM is an important resource for all countries, even those without nuclear material. **Ms. Silagadze** concurred with the audience polling results and offered details on the importance of effective and enforceable legislation. Mr. Herbach discussed some of the benefits of participation in the CPPNM and A/CPPNM. In addition to the legal obligations of the Convention, which require State Parties to inform the IAEA of their laws and regulations that give effect to the Convention, the IAEA also offers an assistance programme for drafting, reviewing and revising national and regulatory laws to meet the standards of the CPPNM. Mr. Herbach also mentioned the IAEA Handbook on Nuclear Law [6], which includes model legislation.

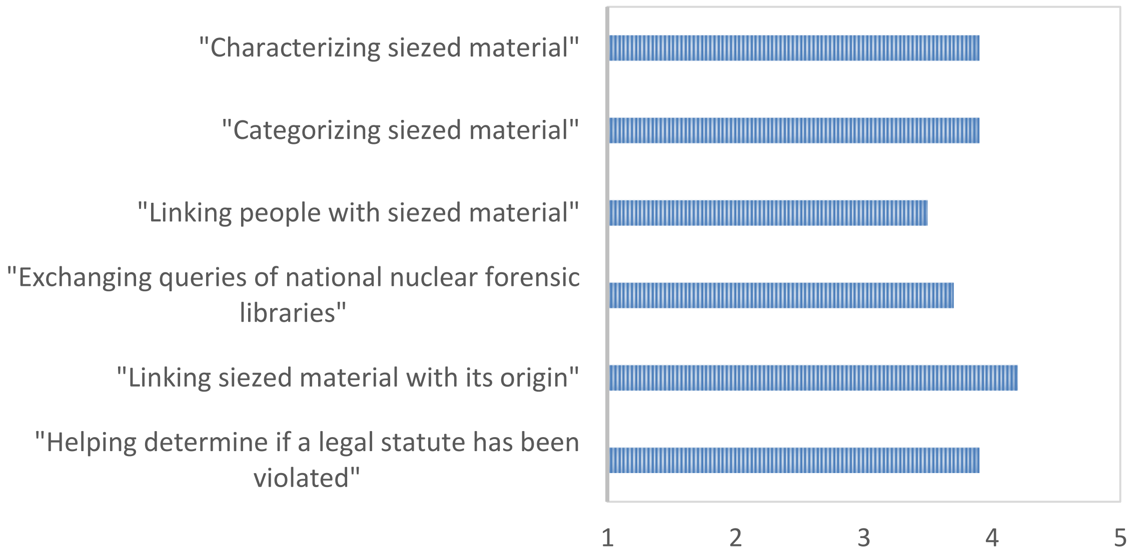
The second audience poll of the session invited participants to assess the relative impacts of the provision of nuclear forensics on A/CPPNM obligations, on a scale of one to five. The results of audience polling are shown in Fig. 1. A total of 77 responses were received from the audience.

Panellists also provided remarks, with Ms. Silagadze indicating that the linking of people with seized material is a critical aspect of a criminal investigation. Ms. Nilsson agreed that connecting people to the seized material is an important aspect of the investigation, but she also emphasized the importance of linking seized material to its origin so as to trace weaknesses in the nuclear security infrastructure, in accordance with A/CPPNM Article 5 (2b), which states that:

“…the States Parties concerned shall exchange information with each other, the International Atomic Energy Agency and other relevant international organizations with a view to protecting threatened nuclear material, verifying the integrity of the shipping container or recovering unlawfully taken nuclear material… [and] … ensure the return of recovered nuclear material stolen or missing…” [4].

It was also highlighted that in the context of returning nuclear and other radioactive material out of regulatory control to its owner, the ability to include or exclude the likely origins of material using nuclear forensics could assist States Parties in meeting their obligations under Article 5, 2b(iii). Mr. Herbach indicated that he finds the criminalization aspect to be important in that it helps to determine if a legal statute has been violated.

Final discussion during the session was spurred by audience questions. First, one audience member asked if the panellists viewed any specific provisions as more important for a State to support nuclear forensics. Ms. Nilsson noted that all States need to have some kind of characterization capability, but that perhaps not every State needs a more advanced capability, while Ms. Silagadze encouraged those developing a nuclear forensic capability to reach out to the international community for assistance. Another audience member asked if it is more important to determine where material is produced or where the material was lost from regulatory control. Ms. Silagadze responded that both are important, and Mr. Herbach clarified that one is a security issue and the other is a potential criminal issue, making comparison difficult.



Note: Collated averaged responses are shown from participating audience members.

FIG. 1. Participant assessment of the provision of nuclear forensics as they impact A/CPPNM obligations.

2.3.3. Panel discussion 2 — Nuclear forensics during the COVID-19 pandemic

Moderated by **Mr. Jeremy Edwards** (UK), this panel discussion focused on the impacts of the COVID-19 pandemic on the field of nuclear forensics. The panellists were Mr. David Smith (USA), Ms. Ruth Kips (USA), Ms. Jovana Nikolov (Serbia), Ms. Puck Brandhoff (Netherlands) and Ms. Erica Wolf (USA).

Mr. Smith remarked that the COVID-19 pandemic had brought about an entirely new playing field, noting that his colleagues at the Lawrence Livermore National Laboratory (LLNL) were able to pivot quickly and relatively seamlessly to virtual engagement. Mr. Smith also referred to the virtual convening of the NuFor — Nuclear Forensics Conference, organized by the Institute of Physics, UK in 2021, which he complimented as having been smoothly run and engaging. Finally, Mr. Smith commended the ITWG for its deft transition to virtual events and engagements, which maintained the momentum of the group and allowed greater access from a geographic standpoint.

Ms. Kips, also from LLNL, then provided some follow-up to Mr. Smith’s remarks, and elaborated on engagement among early and mid-career professionals throughout the discipline. Ms. Kips reiterated the impactful shift from frequent, in-person interactions to virtual only communication, which is particularly difficult in laboratory jobs. Ms. Kips also noted that the barriers for entry of early career professionals (i.e. acting as an observer during a meeting or training) are much lower when events are held virtually, since participation does not necessitate a budget for travel and accommodations. As such, new entrants to the field of nuclear forensics were able to learn first hand, from their home offices, how LLNL staff contribute to international training and engagements.

Ms. Nikolov discussed some of the challenges associated with the COVID-19 pandemic, primarily in terms of the inability to encourage participation in practical exercises and scenarios when gathering groups of people was considered unsafe. She noted that certain aspects of the training could be converted to virtual engagement and involve all interested staff; however, she remarked on the difficulty of focusing on virtual material in the face of potential distractions in the location of the virtual participant.

When asked about her own reflections on the challenges and opportunities resulting from COVID-19, **Ms. Brandhoff** described the completion of the Analytical Plan Development Workshop organized in cooperation with the USA. The workshop was delivered by the Office of Nuclear Smuggling Detection and Deterrence (NSDD) within the DOE National Nuclear Security Administration. Ms. Brandhoff also remarked that more participants were included as a result of the virtual format. She noted some positive aspects in relation to scheduling: because of the virtual format, the workshop was conducted in sessions of approximately three hours over the course of three consecutive days, allowing participants to be fresher and more attentive while also being able to keep up with other aspects of their work. Ms. Brandhoff also underlined the value of employing an interactive presentation software during virtual events so as to increase engagement and counterbalance the loss of immersive engagement characteristic of in-person events.

Mr. Edwards then prompted the panellists to answer the following question: In the move to virtual or hybrid conferences and courses, have you given more thought to the overall learning experience? Ms. Brandhoff answered in the affirmative, noting that trainers need to make better use of the time and work diligently to make the material more engaging. Mr. Smith shared his experience with a nuclear forensic investigation at the UK National Nuclear Laboratory. He indicated that nuclear forensic experts sometimes assume that everyone is familiar with nuclear forensics, but nuclear forensic experts need to remember to convey the importance of the discipline to the rest of the nuclear world. As a representative of NSDD, **Ms. Wolf** discussed their work with over 80 countries, along with some additional partners during the pandemic. She outlined some of the ways to tailor one’s approach to virtual engagement. Because personnel do not have to travel, they are able to undertake outreach activities more directly with new partners, without having to manage logistics and travel arrangements, which can sometimes be a barrier. Ms. Wolf also noted the benefits of regular and scheduled engagements, when carried out in a virtual environment.

Mr. Edwards noted that the panellists and other presenters at the technical meeting demonstrated that training can be sustained and that outreach can be increased during a global health emergency. He asked what other tools and metrics have been applied to measure success. Ms. Kips echoed previous comments, confirming that interactive presentation software is a highly useful tool. Ms. Kips outlined efforts undertaken by her team to condense course contents in an effort to reduce time spent online. She also remarked that measurements and metrics are not a challenge only during virtual workshops, as engagement can sometimes be low during in-person workshops as well. The ultimate goal, Ms. Kips stated, is to establish, develop and maintain a network of nuclear forensic practitioners. While there were some challenges with the shipping of forensic samples during the COVID-19 pandemic, ultimately these samples were able to arrive at their intended destinations. Ms. Nikolov noted that her organization in Serbia only held one training session during COVID-19, but that virtual training was well supported by experts from the European Commission. Despite all of the benefits of virtual initiatives, Ms. Nikolov reported that participants had nevertheless indicated that they would prefer in-person training.

2.3.4. Panel discussion 3 — From crime scene to courtroom

Mr. John Buchanan moderated the third panel discussion, entitled ‘From crime scene to courtroom’, with panellists **Ms. Puck Brandhoff** (Netherlands), **Mr. Ed van Zalen** (European Commission), **Mr. Elder Magalhães de Souza** (Brazil) and **Ms. Maia Silagadze** (Georgia). Mr. Buchanan began the discussion with a focus on the prosecutor’s needs. He outlined a hypothetical scenario for the panellists and audience to consider, in which a fictitious person was arrested while attempting to remotely detonate a radiological dispersal device (RDD) using a mobile telephone. In this scenario, the explosives have been deactivated, but the material is contaminated with ^{137}Cs. In addition, a locker used by the suspect was found to contain material consistent with the RDD, and also contaminated with ^{137}Cs.

Mr. Buchanan asked prosecutor Ms. Silagadze what crimes had been committed and, from the prosecution side, what evidence would be needed to prosecute the case. Ms. Silagadze listed illegal purchase, possession, storage and use of radioactive material, as well as an act of terrorism in the attempt to remotely detonate the RDD. The types of evidence needed in the court include both traditional forensic evidence and nuclear forensic evidence. Ms. Silagadze also spoke of the importance of technological forensic evidence, such as digital evidence (e.g. photos, videos, emails, text messages) from the mobile telephone. Through these different forms of evidence, the suspect could be linked to the scene and could potentially be prosecuted.

In a follow-on question, Mr. Buchanan asked Mr. van Zalen what types, if any, of nuclear forensic evidence could be used to link the suspect to both scenes (i.e. the RDD location and the storage locker). Mr. van Zalen suggested first focusing on traditional forensic evidence, such as DNA or fingerprints, since nuclear forensic signatures are more difficult to attribute to a single origin or source. Mr. Buchanan helped to highlight the importance of both traditional forensic evidence and nuclear forensic evidence as cases move towards prosecution.

Mr. Buchanan then asked Mr. Magalhães de Souza whether the ^{137}Cs at both of the scenes could be declared ‘the same’. Mr. Magalhães de Souza explained that determining the answer to that question would depend on a very specialized type of analysis, which includes measuring the ratios of other elements, but he also noted that any findings about the two ^{137}Cs samples would be valuable to the investigation. Activity and dose rate readings alone are not sufficient to declare a common source. Mr. Buchanan then posed the following question to Ms. Silagadze: In order to prosecute, what degree of certainty would be needed in relation to the ^{137}Cs samples to demonstrate origin from a common source? She acknowledged that 100% certainty is not an achievable standard, but noted that a nuclear forensic finding indicating ‘likely’ or ‘similar’ origins would be of value.

On the topic of hypothetical challenges by the defence attorney, Mr. Buchanan asked Mr. Magalhães de Souza if sufficient material would be present for both the defence and the prosecution to perform testing. Mr. Magalhães de Souza pointed out that non-destructive analyses would allow both parties to have access to the material. Mr. Buchanan then asked Ms. Brandhoff how long it might take for the defence to conduct a full analysis of the forensic evidence. Ms. Brandhoff explained that it could vary in accordance with the case, and depending on the techniques that the prosecution employs. It would also assume that sufficient sample material had been retained. For example, participants in the Collaborative Material Exercises (CMX) organized by the ITWG are given two months to generate a report. With both the prosecution and the defence having two months (i.e. a total of four months), Mr. Buchanan asked Ms. Silagadze if that timeline would be a challenge, with Ms. Silagadze responding that it could be something to consider but that it would not be prohibitive to the appropriate resolution of the case.

Mr. Buchanan then turned to Mr. van Zalen for further discussion on managing traditional forensic signatures of material that is contaminated, asking about the difficulty of analysis and of the presentation of evidence in the court system. Mr. van Zalen spoke of the work necessary for additional safety precautions when dealing with material contaminated with radionuclides. He went on to mention that building a case often involves multiple steps, saying that nuclear material can be described as ‘similar,’ but that declaring two materials to be ‘the same’ is often impossible.

Mr. Buchanan followed up by asking Ms. Silagadze what challenges are present from the prosecutorial side when presenting nuclear forensic evidence. Ms. Silagadze noted that the forensic scientists who help to analyse the evidence and generate the report will also have to testify in court and that a strong testimony with clear and simple explanations of the scientific concepts will be key to success. Furthermore, Ms. Silagadze explained that the radioactive nature of the evidence poses safety concerns, and therefore the physical evidence cannot be brought into the courtroom. As such, the strength and clarity of the report is of utmost importance.

When prompted for final thoughts and guidance from the panellists, they highlighted the importance of effective and frequent communication between all parties from various disciplines. Mr. Buchanan then opened the floor for questions and comments. One audience member noted that the defence cannot run its own analysis of evidence. Rather, material considered as evidence is analysed by a certified laboratory, and the findings are treated as fact.

2.3.5. Panel discussion 4 — Success stories in nuclear forensic capacity building

A panel discussion was convened on success stories in nuclear forensic capacity building in States. The panel consisted of Ms. Liz Dallas (USA), Mr. Manny Mathuthu (South Africa), Mr. Ivalyo Ivanov (Bulgaria) and Mr. Viktor Gluchshenko (Kazakhstan). Mr. David Smith (USA) acted as the moderator.

Ms. Dallas considered the different approaches that States have taken in the development of national nuclear forensic capabilities. She noted that some States have taken a top-down approach, where the development of nuclear forensics is driven by policymakers and implemented by technical personnel. In other cases, States have taken a grassroots approach, where scientists and law enforcement have communicated the importance of a national nuclear forensic capability upwards to policymakers, while taking steps to implement nuclear forensic capabilities at the technical level. She explained that both approaches have benefits, and she encouraged States to do whatever works best within their nuclear security framework. She also discussed the importance of using metrics in the assessment of efforts to build capacity in nuclear forensics. In her office, the United States Department of Energy (DOE), well defined metrics are essential for determining the allocation of resources in current and future nuclear forensic activities. Finally, she highlighted the role that a national nuclear forensic ‘champion’ can play in the development of nuclear forensics within a State. This champion can work across different offices, divisions and organizations within the State, and can promote the importance of nuclear forensics to key policymakers and other stakeholders within the State.

Mr. Mathuthu described the prioritization of the development of a national nuclear forensic library in South Africa as the primary area that concerns capacity building. In order to develop the library, resources from national science funding sources were sought and procured. Further capacity building efforts have focused on the development of human resources, particularly in graduate programmes. South Africa has also participated in exercises, including those organized by the Nuclear Forensics ITWG, and in the IAEA Nuclear Forensics Residential Assignment programme.

Mr. Ivanov provided the Bulgarian point of view, on the basis of a risk informed approach. As a State on the border of both Europe and Asia, and as a European Union border State, Bulgaria is considered a high risk transit zone for nuclear or other radioactive material out of regulatory control. As a user, but not a producer, of nuclear material (e.g. low enriched uranium), he explained that the Bulgarian approach to nuclear forensics focuses on the material used in the State. He also explained the recent reorganization of standard operating procedures in response to incidents involving the detection of nuclear or other radioactive material out of regulatory control. New standard operating procedures were therefore introduced, for example on the analysis of orphan sources and the response to the illicit transport of nuclear or other radioactive material. Tabletop exercises have been organized in order to assess the effectiveness of the new standard operating procedures, and these will take place in the coming years. Finally, Mr. Ivanov highlighted the need for increasingly strong links between scientific organizations, law enforcement — including prosecutors — and stakeholders in nuclear security responses so as to ensure that nuclear forensics can be implemented in support of nuclear security.

Mr. Gluchshenko described the evolution of Kazakhstan's nuclear forensic capabilities since the need for such capabilities was first identified approximately 25 years ago. Since then, Kazakhstan has established itself as a leader in nuclear forensics, and can now analyse a wide variety of nuclear or other radioactive material out of regulatory control that is encountered in Kazakhstan. He noted that, on the subject of building capacity in nuclear forensics, "the real world is the best teacher". He further indicated that Kazakhstan understands the need for high quality and reliable nuclear forensic data that can be used in legal proceedings. Finally, Mr. Gluchshenko discussed the need for continued communication between all of the stakeholders involved in nuclear forensics. He described some of the ongoing engagements that Kazakhstan has with other organizations on this issue, and discussed how different agencies have become involved in nuclear forensic exercises.

2.3.6. Panel discussion 5 — Experiences with the self-assessment tool of the Global Initiative to Combat Nuclear Terrorism

This panel discussion, moderated by Mr. Kevin O'Prey (USA), centred on the development of the self-assessment tool (SAT) by the Global Initiative to Combat Nuclear Terrorism (GICNT) and its use by States in the development of their capabilities in nuclear forensics. The panel consisted of Mr. Andrei Apostol (Romania), Mr. Ali El-Jaby (Canada) and Ms. Harinate Mungpayaban (Thailand).

Mr. El-Jaby described the origins of the SAT, which began at the 2015 Plenary Meeting of the GICNT. He elaborated on the tool, which is a worksheet based information collection and integration tool designed to assist States in the structuring of inter-agency efforts to perform an inventory of, and assess, national nuclear forensic capabilities. The tool is used to establish or enhance nuclear forensic capabilities, in part through an identification of gaps in capabilities. He highlighted that use of the SAT is entirely voluntary and is not intended to be binding in any way. The SAT has been successfully implemented since its development in 2015. Moreover, States have no obligation to share the information that they collect using the SAT. When providing guidance to States interested in using the SAT, he noted that, like any self-assessment, use of the tool is not a 'one and done' process. Rather, its use can be part of a longer term effort. The tool can be used even as the national nuclear security landscape evolves over time.

Mr. Apostol noted that one major strength of the SAT is that it was developed by subject matter experts in nuclear forensics. The tool was designed using a 'traffic light' concept, with green indicating that a particular aspect of nuclear forensics is already established, red indicating that a particular aspect is not yet established, and yellow indicating that an aspect of nuclear forensics is in progress of being established or is otherwise incomplete. Use of the traffic light system helps non-technical policymakers identify gaps and understand where resources can be spent in order to address these gaps. Mr. Apostol also highlighted the value that the SAT serves in getting all of the stakeholders together to communicate and understand the various roles and responsibilities that they could hold in the case of an incident involving nuclear or other radioactive material out of regulatory control. The use of the SAT in Romania has led to the creation of a nuclear security working group and the development of a national response plan. In part through use of the SAT, Romania has been able to greatly increase the number of cases prosecuted for illicit smuggling of nuclear and other radioactive material.

Ms. Mungpayaban described how use of the SAT in Thailand led to the identification of gaps in national nuclear forensic capabilities. In part through use of the information collected using the SAT, stakeholders were able to report nuclear forensic needs to policymakers, which has led to a significant reduction in capability gaps. Ultimately, nuclear security stakeholders were able to develop a roadmap and comprehensive framework for nuclear forensics by involving all key stakeholders, from those involved with the management of radioactive crime scenes to technical staff involved in nuclear forensics, regulators and legal authorities. She noted, however, that one key challenge had to do with language: Thailand had the SAT translated into Thai to facilitate its use by all stakeholders.

2.3.7. Panel discussion 6 — International assistance and partnerships in nuclear forensics

This panel discussion, moderated by Mr. Ed van Zalen (Netherlands), centred on the status and outlook of international assistance and partnerships in the context of nuclear forensics. The panel consisted of Mr. Andrei Apostol (Romania), Mr. Michael Curry (USA), Mr. John Buchanan (Interpol), Mr. Talgat Toleubayev (United Nations Interregional Crime and Justice Research Institute — UNICRI) and Mr. Daming Liu (IAEA). Mr. van Zalen first recalled the Nuclear Security Summit (NSS) in 2016, at which time participants agreed that NSS efforts would be jointly supported by the IAEA, Interpol, UNICRI, the ITWG and the GICNT. Today, he noted the emphasis on connecting nuclear forensics with radiological crime scene management and facilitating communication between experts, law enforcement officials and prosecutors.

Mr. Apostol, Co-chair of the Nuclear Forensics Working Group of the GICNT, discussed continued efforts of the GICNT to promote the importance of implementing national legislation to address criminal or other intentional unauthorized acts involving nuclear and other radioactive material outside of regulatory control. Many events and exercises have been organized by GICNT to bring together scientists, law enforcement officials and policymakers so as to advocate the implementation of these laws at the national level. Mr. Apostol also highlighted the increase of successful investigations into, and judicial proceedings against, acts carried out in Romania involving nuclear and other radioactive material, and he emphasized the benefit of using the GICNT self-assessment tool.

Mr. Curry, representing the ITWG, explained that since the organization's inception in the 1990s, members have been well aware of the importance of involving science in incident investigation, but the connection between science and law enforcement was less developed thirty years ago. He noted that recent CMX, and particularly CMX-7, have been very useful in forging these important connections by involving law enforcement in the exercise, as well as by incorporating a traditional forensic component. Furthermore, Mr. Curry clarified that the ITWG does not have a formal partnership with other organizations or entities, but continues to create opportunities for CMX participants to bring what they have learned through CMX exercises to their home countries, to develop nuclear forensics, build capacity and forge connections with law enforcement and other stakeholders. Exercises also help build awareness among policymakers, prosecutors and other stakeholders.

In his remarks, **Mr. Buchanan** underscored that Interpol is very focused on information sharing. The organization's five working groups are the main mechanisms to understand the different types of incidents involving nuclear and other radioactive material, to discover lessons and to then fold the information into capacity building efforts. Interpol brings together the stakeholders necessary to develop targeted, focused training courses that complement those offered by the UNICRI, IAEA and other organizations.

Mr. Toleubayev, from the UNICRI, expressed his gratitude to the IAEA technical meeting coordinators for bringing stakeholders together. He noted that the UNICRI, together with the Organization for the Prohibition of Chemical Weapons and the International Association for Prosecutors, had recently produced a prosecutor's guide for chemical and biological crimes. UNICRI is now working on a similar guidebook for the prosecution of crimes involving nuclear and other radioactive material, which has benefited from constructive conversations with experts at the technical meeting, including with personnel from the IAEA, the GICNT, the ITWG and JRC-Karlsruhe. These guidebooks have been produced by subject matter experts, with UNICRI involving experienced prosecutors from many different countries with diverse types of law. UNICRI also has a laboratory, which simplifies some aspects of the chain of custody, as well as the relationship with the academic community. He concluded by emphasizing the importance of using guidance documents in capacity building activities (e.g. education videos, eLearning modules).

Mr. Liu, from the IAEA Materials Outside of Regulatory Control Section, stressed that the Nuclear Security Plans developed by the IAEA since 2003 play an important role in shaping the role of the IAEA in global nuclear security. Nuclear forensics has been integrated in all nuclear security plans since that time. Mr. Liu also stated that the IAEA has established an Integrated Nuclear Security Support Plan (INSSP) with over 130 Member States, which is designed to identify gaps and help meet State needs. As a technical organization, part of the IAEA's responsibilities is to provide support and training so as to improve State capabilities in detection and response.

In this panel discussion, the panellists underscored the importance of communication between scientific experts, policymakers and law enforcement officials, which can take place at meetings such as the technical meeting, as well as through ITWG CMX or GICNT workshops and tabletop exercises. Connections can also be made through the use of self-assessment tools, and by pursuing international assistance and establishing partnerships with groups and agencies, such as the IAEA, GICNT, ITWG, UNICRI and Interpol. The session highlighted the evolution in the relationship between the nuclear forensic science community and those in policy and law enforcement over the past 20–30 years. Mr. van Zalen concluded the session with two open questions: How will the community go about training technical experts to give testimony in court, and is there any overlap in present or planned training offered by represented groups?

2.3.8. Panel discussion 7 — The future of nuclear forensics

This panel discussion, moderated by Mr. Kevin O'Prey (USA), brought together a geographically diverse panel of experts to discuss the future of nuclear forensics. The panellists included Ms. Alina Nitrean (Moldova), Mr. Askar Nabi (Kazakhstan), Ms. Tegan Bull (Australia), Mr. Ike Dimayuga (Canada) and Ms. Naomi Marks (USA).

Remarks from **Ms. Nitrean** included a reminder that nuclear forensics is not only important for the examination of the nuclear material itself but also for the connection of this material to people or events. Participation in activities, such as the CMX, as well as the development of methods to analyse the signatures associated with nuclear and other radioactive material, provides high value opportunities to apply nuclear forensic techniques so as to effectively support subsequent investigations. Ms. Nitrean also commended the speakers who were presenting on radiological crime scene management at the technical meeting, emphasizing that information on radiological crime scene management is useful for helping the community to understand best practices. She underlined the importance of intelligence as a starting point for an investigation, as well as considerations in relation to how information is presented in court.

Mr. Nabi described the fight against illicit trafficking in Kazakhstan, as the global leader in uranium mining and uranium reserves. Kazakhstan also partakes in research on nuclear material. He described the suppression of the activities of a transnational criminal group in 2021, but said that State officials remain aware of the unpredictable nature of adversary capabilities. Currently, a project is in preparation at a regional centre for nuclear forensics, and its successful implementation will result in the development of an expert group and a series of online and offline meetings. Mr. Nabi summed up his presentation by saying: "Crime has no boundaries, and so nuclear forensics should develop without limits."

When prompted to discuss game changing, novel technologies, **Ms. Bull**, from the Australian Nuclear Science and Technology Organisation (ANSTO), provided the example of the development of radiation sensor technologies for use by first responders and frontline officers, as well as the transfer of radiation sensor technology to the laboratory setting. She also cited as a future development the integration of radiation protection into crime scene instruction through augmented reality technology, which would enable the visualization of radiation in real time. Ms. Bull described the possibility of employing virtual reality in training and development, which could perhaps also be used in a courtroom to better convey information to the jury or others in the court. She mentioned an ANSTO developed radiation imaging solution technology for visualizing gamma radiation at a crime scene. As an additional future development, Ms. Bull also described the use of rapid DNA analysis of evidence contaminated with radionuclides. She concluded her remarks by acknowledging that the development and implementation of these new technologies will come with challenges and competition for resources, and she noted the importance of preparing to present the results of the different techniques in a court of law.

Mr. Dimayuga followed with remarks on the challenges of deploying novel technologies. He noted that much work has been undertaken throughout the nuclear industry in preparation for the deployment of novel nuclear technologies (e.g. small modular reactors, advanced modular reactors). Mr. Dimayuga explained that having different types of fuel means that users need different types of analytical techniques to measure the nuclear forensic signatures of the material. He noted a rare opportunity to develop these signatures in parallel with the fuel selection and manufacture process associated with the development of advanced reactors, making the modern day a very exciting time for the community, but also challenging from a technical standpoint.

When asked about actions that States could take to promote a next generation of nuclear forensic scientists, **Ms. Marks** described a number of strategies for addressing human capital in the field. Beyond recruiting new staff among the conference attendees' respective institutions, she asked participants to think of ways to involve potential nuclear forensic scientists and stewards in the earlier stages, perhaps at the university level. Ms. Marks mentioned some of the more creative ideas, including modifying an exercise, for example the CMX, into a tabletop format, and using gamification and other engaging approaches to reach, educate and recruit early career individuals and groups. She also emphasized the need for sufficient training within organizations, so that when one scientist departs from an institution, qualified people are prepared to replace the scientist. Training multiple nuclear forensic practitioners also allows staff to accept opportunities, such as fellowships, residential assignments, internships and other positions at the IAEA. Ms. Marks also underscored the importance of early and consistent engagement and mentorship.

The five panellists in this session presented a wealth of exciting future developments and ideas for engaging junior staff, while remaining mindful of the challenges associated with such critical developments. The future of nuclear forensics, the panellists shared, centres on characterizing novel material used in the nuclear industry, relaying technological advances in a court of law and building a depth of institutional knowledge among staff contributing to all of the elements of nuclear forensics. The panellists emphasized the importance of continuing existing work, while identifying opportunities for growth or repurposing, for example in the case of tabletop exercises such as the ITWG's CMX.

2.3.9. Panel discussion 8 — Nuclear forensic findings

This panel discussion, moderated by **Mr. Kevin O'Prey** (USA), focused on nuclear forensic findings. In lieu of individual questions for the panellists, Mr. O'Prey posed broader questions to the panel and allowed all of the members to provide an opinion. The panel comprised **Ms. Kathleen Heppell-Mays (Canada)**, from the Canadian Nuclear Safety Commission, and **Mr. Jay Tilden** and **Ms. Erica Wolf (USA)**, both from the National Nuclear Security Administration.

The panellists were first asked what they viewed as the greatest accomplishment in nuclear forensics and radiological crime scene management, as key components of nuclear security. Ms. Heppell-Mays alluded to Canada's strong nuclear material accountancy system, explaining that understanding State holdings of nuclear material comes down to the important question of: does the interdicted nuclear or other radioactive material belong to the State and has a crime been committed? She also described the importance of investing in people and investing in science, technology, engineering and mathematics (i.e. the STEM fields), as it builds and sustains a nuclear forensic capability. Ms. Wolf echoed Ms. Heppell-Mays' points and also emphasized that strong investment in a nuclear forensic capacity could be achieved through national legislation. While the creation and adoption of national legislation could take a long time, Ms. Wolf noted that capacity building, along with the use of self-assessment tools, can be enacted over the shorter term. She also stated that nuclear forensic capabilities can exist in many places, including in universities and even in the private sector. As nuclear forensics is a multidisciplinary practice, Ms. Wolf noted that communication between the different stakeholders is key, as are training, workshops, exercises and other elements of engagement to help fill the gaps identified through self-assessment. In his remarks, Mr. Tilden reminded the participants that no State has to believe that it is in a quest to build a nuclear forensic capacity alone. If a State needs more advanced capabilities, it need not hesitate to contact regional or international partners.

When prompted to discuss practical measures that could help nuclear forensics and radiological crime scene management to operate more seamlessly, Mr. Tilden noted that a perfect global nuclear security architecture would render radiological crime scene management non-existent. He underlined that the exercises are nonetheless absolutely essential for sustaining this capability and establishing effective communication between the disciplines that support these capabilities. Ms. Wolf encouraged States to adhere to, or in some cases to develop, a national nuclear security response plan in order to help nuclear forensics and radiological crime scene management operate more smoothly. Ms. Heppell-Mays added the helpful reminder that personnel who work in the courtroom are not the same people as those who work in the laboratory, making the understanding and interpretation of nuclear forensic information by non-experts of utmost importance.

The discussion then shifted to the future of sustaining nuclear forensics and radiological crime scene management over the next 10–15 years, with Ms. Heppell-Mays encouraging the expansion of the pool of experts to incorporate new technologies. Ms. Wolf emphasized that mentoring and fellowships are essential, supporting the capabilities of States that have established nuclear forensic capacities in order to help States that are continuing to build this capability. Mr. Tilden mentioned asynchronous collaboration — for example, through tabletop exercises such as the Galaxy Serpent exercise — as a great way to engage and interact, particularly given the flexibility in work environments brought about by the COVID-19 pandemic.

Audience members were then able to pose questions to the panellists. One participant asked about knowledge management within a system with frequent rotation among law enforcement personnel. Ms. Wolf shared that her organization, the NSDD, has heard a great deal about this issue, as the rotation of personnel is a consistent challenge. The NSDD has found a way to train people virtually and continually throughout the year, and is using regional hubs for this purpose. Mr. Tilden suggested that because rotations are a part of the expected career of most law enforcement officials, seconding personnel to organizations is a good way to build bridges. Ms. Heppell-Mays pointed out that disseminating nuclear forensic knowledge in a system with rotating positions is another way to help spread information, and that trainees could be viewed as ambassadors of nuclear forensics and radiological crime scene management. An audience member then asked whether the field of nuclear forensics can adapt and keep pace as the world confronts energy challenges and looks to different energy sources, including small modular reactors and the thorium fuel cycle. Ms. Heppell-Mays stated that Canada has been a leader in new nuclear technologies, and the country therefore needs time to adjust in terms of associated nuclear forensic signatures. Mr. Tilden added that it is human nature to adapt, noting that the nuclear forensic community has come far in 30 years. He did not anticipate that small modular reactors would be an insurmountable challenge for nuclear forensics, a field in which change and adaptability come naturally.

The final thoughts from the panellists reflected optimism for the field of nuclear forensics. Ms. Heppell-Mays indicated that she has been continually impressed by the field's passion, excitement and willingness to collaborate, while Ms. Wolf expressed her gratitude to the meeting's organizers, as these types of interaction help support major developments in nuclear forensics. Mr. Tilden supported Ms. Wolf's comments and added that the nuclear forensic community has come together through State involvement and the IAEA embracing this mission, providing a place to gather and exchange best practices. He emphasized that the technical meeting is a fantastic 'force multiplier' for all of its participants, showing that those organizations represented at the technical meeting are leading the charge.

2.3.10. Key themes emerging from the panel discussions

In the technical meeting panel sessions, the speakers underscored the importance of communication and collaboration between scientific experts, policymakers, law enforcement and prosecutors, under such frameworks as the CPPNM/A and the GICNT self-assessment tool. Themes also centered on the future of nuclear forensics, including the future application of innovations brought about by the COVID-19 pandemic and the continued value of international assistance and partnerships.

2.4. TECHNICAL SESSIONS

The technical sessions that were convened during the meeting covered a wide array of topics and demonstrated the breadth of nuclear forensic examinations in the context of global nuclear security.

2.4.1. Technical session 1 — Legal framework and the Convention on the Physical Protection of Nuclear Material (CPPNM) and its Amendment (CPPNM/A)

Mr. Jerry Davydov (USA) gave a presentation on the use of nuclear forensic capacities to support national enforcement of, and demonstrate compliance with, international legal instruments concerning nuclear counterterrorism. In his presentation, Mr. Davydov connected the implementation of nuclear forensic capabilities to the enforcement of national laws that pertain to nuclear and other radioactive material out of regulatory control, particularly in the context of international legal instruments concerning nuclear counterterrorism. He provided historical context and mentioned the key players in the development of the international nuclear counterterrorism legal framework from 1980 to today. He then highlighted complementary IAEA publications in the Nuclear Security Series, in particular Nos 37-G, Developing a National Framework for Managing the Response to Nuclear Security Events [7], and 2-G (Rev. 1), Nuclear Forensics in Support of Investigations [8]. Nuclear forensics, Mr. Davydov indicated, helps to support national and international nuclear counterterrorism law through criminalization, jurisdiction, prosecution and extradition, as well as through legal cooperation, assistance and information sharing.

Ms. Vallerie Ann Samson (Philippines) discussed collaboration between ANSTO and the Philippine Nuclear Research Institute (PNRI) concerning nuclear forensics and border protection. Following a brief introduction on the two research institutes, Ms. Samson outlined the in-person and virtual engagements undertaken between ANSTO and PNRI, and then described the scientific, technical and regulatory divisions at PNRI, along with their capabilities. Cooperation between the two research institutes has enabled PNRI to join the Nuclear Forensics ITWG and participate in CMX and activities. Additional outcomes from this partnership include collaborative projects on border protection, inspection, radioactive tracers and future projects that are in the development stages.

Ms. Jovana Nikolov (Serbia) gave an overview of criminal legislation and nuclear forensic capabilities in Western Balkan countries. She first introduced the Western Balkan countries — Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia — and explained that none are presently in the European Union, but that all have signed and ratified multiple international treaties in support of nuclear safeguards and forensics. Ms. Nikolov explained the developing national legal framework in the region, citing Serbia as a representative example. She then shared information on collaborative training and capacity building efforts that are ongoing in the region, including workshops and online training. She concluded her presentation with a proposal to engage the region in nuclear forensic opportunities, for example in the GICNT, or in the CMX or similar exercises, as a region, and she encouraged the development of national action plans.

Mr. Ababacar Sadikhe Ndao (Senegal) reviewed the challenges in establishing and maintaining a national nuclear forensic support framework and the importance of international cooperation. Mr. Ndao indicated that Senegal has no nuclear installation or waste management facilities, nor any uranium ores that have not been mined. However, there is interest in both developing a research reactor and increasing protection against terrorist attacks. Mr. Ndao then outlined the regulatory structure in Senegal and the ways in which radioactive materials are managed and controlled. He shared a graphical representation of the types of nuclear and other radioactive material known to, and regulated by, the Senegalese government. Mr. Ndao then outlined the opportunities that have been seized by his Senegalese colleagues, including participation in in-person IAEA training courses on nuclear forensics. These events have helped to bring relevant stakeholders in Senegal together for training. In addition, Mr. Ndao provided details on the existing analytical capabilities in Senegal, which can be leveraged to support a nuclear forensic programme. Finally, Mr. Ndao acknowledged some challenges, for instance adding nuclear forensic training to the police academy, increasing the amount of available equipment, and developing a national system for prevention, detection and response.

Mr. Ramin Pashavyev (Azerbaijan) presented on the activities of the regulatory authority in support of nuclear forensics. He began by outlining the necessary regulatory components, including the presence of a regulatory body and a legislative framework, the use of nuclear forensic science facilities and expertise, training of law enforcement officials, and the establishment of internal collaboration. Mr. Pashavyev provided information on Azerbaijan’s National Nuclear Research Center, created in 2014, which also houses the Nuclear Forensics Laboratory in Azerbaijan. He also described the establishment in 2008 of Azerbaijan’s State Agency on Nuclear and Radiological Activity Regulations and outlined its primary responsibilities in the realm of nuclear forensics.

Mr. Nigel Tottie (IAEA) concluded the session by discussing the role of radiological crime scene management and nuclear forensic science in a State’s national response framework, referring participants to the IAEA Nuclear Security Series as a whole, and more specifically to Ref. [7]. Mr. Tottie emphasized that the response to a nuclear security event has to support any subsequent legal proceedings, which will focus on functional outcomes, including information gathering; information analysis; notification, action and deployment; counteraction; investigation; public information and the mitigation of consequences. Mr. Tottie further connected the national response framework to both radiological crime scene management and nuclear forensics, specifically in the case of investigating nuclear security events and regaining control of material out of regulatory control. To close, Mr. Tottie provided a clear explanation of the ‘response roadmap’, a method that his team at the IAEA uses with States to take a phased approach to developing a national framework for response capabilities.

2.4.2. Technical session 2 — Capability development and sustainability

Mr. Péter Völgyesi (Hungary) chaired this session and began by welcoming **Ms. Karen Kennedy** (UK), who presented the UK case study to build and maintain an enduring nuclear forensic provenance capability. Ms. Kennedy underlined that her colleague, Jeremy Edwards, was an equal contributor to the development of this case study. She then provided background on military and civil occurrences of the detection of nuclear or radioactive material out of regulatory control, as well as those cases that are ‘grey’ (i.e. unknown). She then outlined the framework for the hub and spoke model used in the UK (jointly created by the Atomic Weapons Establishment and National Nuclear Laboratory) to call on expertise to build an integrated response to such incidents. Ms. Kennedy noted certain advantages of the model, including the minimization of duplicate assessments, as well as some of the potential challenges, including logistical issues when communicating between different agencies and experts. She provided details on an exercise conducted in early 2022 to test the new model structure, which was an overall success. Ms. Kennedy also noted that participants provided practical feedback on areas in need of improvement.

Mr. Jerry Davydov (USA) then presented on using an NNFL to address gaps within a nuclear security infrastructure, describing how NNFLs provide States with mechanisms to make determinations about their own nuclear security infrastructure. Mr. Davydov emphasized that an NNFL is built on both reference information and subject matter expertise. He proceeded to describe three broad categories of nuclear forensic examinations: (1) those in support of law enforcement and prosecutorial bodies trying to determine if an infraction has occurred; (2) those that necessitate technical evidence, detailed material analysis, and intercomparison to support prosecutorial bodies and regulatory investigators in their investigations; and (3) those that support international investigations, necessitating collaboration and information sharing. Mr. Davydov emphasized that, much like other aspects of a State's nuclear forensic capacity, an NNFL is an essential part of a national response plan.

Mr. Yoshiki Kimura (Japan), from the Integrated Support Center for Nuclear Nonproliferation and Nuclear Security at the Japan Atomic Energy Agency (ISCN-JAEA), provided a virtual presentation on the current status and future prospects of nuclear forensic capability building and technology development. The ISCN has been operating in Japan since 2011 with the broad goal of supporting capacity building and analytical expertise in Japan. The first three years of operation focused on radionuclide measurements and prototyping a nuclear forensics library. Years four to six were dedicated to enhancing laboratory capability and developing advanced imaging capabilities for particle samples. From 2018 to the present, the ISCN-JAEA nuclear forensic technology developments have centred on post-dispersion nuclear forensics and the application of emerging technologies and novel signatures. Mr. Kimura described the successes of mobile, low cost radiation detectors and direction sensitive gamma detectors, and also mentioned the application of artificial intelligence algorithms to nuclear forensic data interpretation. He concluded his presentation by outlining recent examples of international collaboration and cooperation initiatives that the ISCN-JAEA has been involved in, including project arrangements with DOE laboratories, information exchanges with JRC-Karlsruhe, participation in ITWG exercises, and comparative and joint sample analyses projects involving multiple nations.

Mr. Adam Stratz (USA) discussed nuclear forensic expert pipeline sustainability as a key component of nuclear security. Mr. Stratz first provided background information on the efforts of his organization, NSDD, which include capacity building activities and peer to peer exchanges. He further explained that the specific support categories with the NSDD in relation to capacity building are national response plans, categorization, characterization and NNFLs. Each of these categories, he explained, relies on human capital and the development of expertise. Mr. Stratz shared information about the applicants selected for the International Nuclear Forensics Fellowship, which is supported by the NSDD. The first four recipients of the fellowship are from Armenia, Moldova, Tajikistan and Serbia.

To conclude the second technical session, **Mr. Gary Eppich** (IAEA) presented the IAEA Residential Assignment Programme, which offers first hand nuclear forensic examination training to early career technical and scientific personnel. Mr. Eppich also emphasized that the programme provides collaboration opportunities to both the host and recipient States. He then outlined the steps involved in establishing a residential assignment, from the expression of interest to the end of the assignment and beyond. He also discussed important considerations for the programme, including the duration of the assignment and the training techniques being targeted. The overall aim of the programme is to develop human resources, produce scientific output and strengthen partnerships in nuclear security.

2.4.3. Technical session 3 — Radiological crime scene management

To begin this session, **Ms. Maria Wallenius** (European Commission) presented the hybrid approach of EUSECTRA Remote Interactive eTraining, which is rethinking the practice through an evolution of virtualization. Located at the JRC sites in Karlsruhe, Germany and Ispra, Italy, EUSECTRA conducts training in both nuclear security and nuclear safeguards. Ms. Wallenius explained that, in response to the COVID-19 pandemic, EUSECTRA had worked to strategically virtualize its training in a manner that was engaging and dynamic, while maintaining the live use of nuclear and other radioactive material. This goal was achieved using interactive livestreaming of field exercises and an activity entitled 'Serious Game', where a player enters a scene, selects screening equipment and personal protection equipment (PPE), and then conducts the investigation and evidence collection, mimicking the steps that would be carried out at a true radiological crime scene. Ms. Wallenius stressed that in-person training will not be replaced definitively by such virtual tools, but that their utility in reaching audiences will continue to be valuable moving forward.

Mr. Csaba Tóbi (Hungary) and **Ms. Izabella Kakuja** (Hungary) jointly presented the Hungarian process for radiological crime scene management, explaining its strong legal basis and cooperation between Hungarian authorities, and underlining the need to maintain expertise for potential criminal or other intentional unauthorized events. Ms. Kakuja outlined the individual roles of the radiological crime scene management team and then gave the floor to Mr. Tóbi, who reviewed the key activities of the Hungarian radiological crime scene management procedure and the use of PPE in the context of detailed planning. Mr. Tóbi described the critical steps undertaken at the radiological crime scene, from the initial radiation survey to evidence collection. Finally, Mr. Tóbi highlighted events during which the Hungarian radiological crime scene management procedure has been demonstrated, such as the live demonstration given at IAEA ICONS 2020.

The next presentation, by **Mr. Elder Magalhães de Souza** (Brazil), concerned radiation protection for radiological crime scene management. This presentation focused on the control of radiation exposure of the individuals associated with the radiological crime scene, and particularly those individuals whose primary occupational duties do not regularly expose them to radiation hazards. Mr. Magalhães de Souza suggested the adoption of a system similar to that suggested in the IAEA Safety Reports Series No. 84, Radiation Protection of Itinerant Workers [9], to cover such individuals. He also discussed the importance of clearly establishing the people or entities who are to be responsible for the implementation of safety standards as well as record keeping.

Mr. John Simm (UK) described in his presentation the support of nuclear forensic science to a nuclear security event from the perspective of forensic investigators. He highlighted the importance of considering the forensic strategy when responding to an incident, while maintaining the primary goal of keeping the public safe and preventing further damage. Using an example scenario, Mr. Simm explained how UK police have adapted their standard operating procedures with input from technical and scientific authorities to improve the collection of material and the transfer of this material to the laboratory. Changes include the establishment of a forensic evidence management tent, a central hub for on-site activity, and an interim testing site for high activity material. Mr. Simm highlighted points in the example scenario that demonstrate how the backgrounds and mindsets of law enforcement personnel and forensic science personnel complement each other and provide a richer interpretation of the scene.

Mr. Jack Goralewski (Australia) and **Ms. Nikki Keighran** (Australia) presented virtually on advancements in Australian CBRN training facilities that are giving frontline responders a realistic awareness of working in an area where the radiation dose rate is above a set threshold and the time spent in this area needs to be kept to a minimum. They described their experience contributing to a CBRN capability workshop for Australian first responders and highlighted a new CBRN training facility located in New South Wales, Australia. The workshops are large in scale and provide first responders with realistic experiences working in areas of elevated surface contamination. After introductory lectures, participants are briefed on a scenario and guided through the actions needed to respond. After five minutes or less in the simulated area, participants undergo recovery and decontamination. A second scenario of additional complexity follows.

Finally, **Mr. James Blankenship** (USA) addressed the subject of sustaining the US capability for conventional forensic examination of radioactively contaminated evidence. Mr. Blankenship indicated in his remarks that the laboratory facility in Quantico, Virginia cannot handle radioactive and contaminated evidence. The Federal Bureau of Investigation established a relationship with Savannah River National Laboratory in order to safely and effectively receive, process, store and analyse such material. These needs are of particular importance because evidence might need to be stored until all legal cases are concluded, which could take years to decades.

2.4.4. Technical session 4 — International cooperation and exercises

To lead off the session, **Mr. Jon Schwantes** (USA), from the Pacific Northwest National Laboratory (PNNL), discussed 'Celestial Skónis', the 6th CMX of the ITWG. Mr. Schwantes explained that 21 participants were asked to complete a paired comparison exercise, gathering both nuclear and traditional forensic evidence from real world material (i.e. not reference material). This sixth exercise was noteworthy because plutonium was included in the material, in addition to uranium. He described 'state of practice' observations and measurements, defined as those made by more than half of the participants, as well as emerging technologies, employed by fewer than half of the laboratories within a given time frame. The presentation provided an overview of the exercise structure and participants, in addition to acknowledging the support received from 15 law enforcement agencies.

Mr. Viktor Gluchshenko (Kazakhstan) provided an overview of nuclear forensics in Kazakhstan, and the role of international cooperation in its development. He highlighted the role of the Institute of Nuclear Physics in the country's nuclear forensic approach to combatting the illicit trafficking of nuclear and radioactive material. The institute is licensed for radioactive material, ionizing radiation sources and waste, and it houses a variety of analytical instruments for elemental and isotopic determinations, including neutron activation analysis, X ray fluorescence and ICP-MS. Mr. Gluchshenko also noted instances of international cooperation, as well as the participation of representatives from the Institute of Nuclear Physics in the ITWG and other exercises, including ITWG CMX-7. Finally, Mr. Gluchshenko outlined cooperation initiatives between the Institute of Nuclear Physics and the IAEA in training and exercises.

Mr. Andrei Apostol (Romania) provided preliminary results from the Joint Romania — USA nuclear forensic examination of legacy high enriched uranium (HEU) materials, a project overseen by the Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering (IFIN-HH) and the US laboratories, LLNL and the Los Alamos National Laboratory (LANL). In this joint effort, five selected HEU material underwent a comprehensive nuclear forensic analysis at IFIN-HH, while specific verification analyses took place at LLNL and LANL. Mr. Apostol shared preliminary results that show some distinction between samples in ^{236}U concentration, which were confirmed by measurements at LLNL. He then shared preliminary results from various analytical techniques, including model production dates of ~1969. The project is ongoing, with aliquots taken from two solid samples awaiting shipment to the USA. Overall, this collaboration aims to foster closer cooperation between the IFIN-HH and US laboratories, and to create opportunities for future projects.

Building on the opening presentation from Mr. Schwantes, **Mr. Hubert Schoech** (France) presented on capacity building for nuclear forensics through participation in the ITWG CMX, with a focus on CMX-6 and the ongoing CMX-7. After providing a brief history of nuclear forensics in France since 1995, Mr. Schoech provided background information on the structure of the CMX, including the timelines for reporting findings (e.g. 24 hours, 1 week, 2 months) and the strategic ways in which time was allocated among scientists, police and gendarmerie for gathering forensic evidence. Overall, France anticipates that these types of exercises will serve to bolster nuclear security in anticipation of the Paris 2024 Olympic Games.

Mr. Kirill Zhizhin (Russian Federation) discussed experience in the application of forensic examination techniques in the IAEA regional exercises on nuclear forensics, which focused on interactions between investigators, forensic experts, and nuclear and radioactive material specialists. He described a regional exercise that took place in 2021, in which a fictional city celebration was imagined to be disrupted by a terrorist attack, with the use of multiple types of dispersible radioactive material. These fictional scenario details were also shown in a short video. Mr. Zhizhin then outlined the laboratory analyses of the contaminated material and the environmental samples taken from the different locations. Scanning electron microscopy (SEM) with energy dispersive X ray (EDX) analysis, secondary ion mass spectrometry (SIMS), ICP-MS and traditional forensic analyses were used for this regional exercise. Mr. Zhizhin stressed the importance of formulating investigation questions and discussed how different stakeholders might view the answers to these questions. The exercise also highlighted the importance of communicating conclusions between the parties involved in the investigation.

Ms. Mansie Iyer (USA) provided the final presentation of the session, outlining a series of gamma spectrometry exercises carried out by the NSDD and by LANL. The exercise series, called ‘Spectral Flavor of the Month’, takes place online, with 25 countries and over 60 participants. It has been occurring approximately every other month since the summer of 2020. The aim of the exercise is to bring together existing gamma spectrometry practitioners to regularly employ their gamma spectrometry skills so as to sustain core capabilities and identify gaps. An additional benefit is the improved inter-agency communication that takes place with regular drills. Ms. Iyer also provided feedback and lessons that have been gathered as the programme has developed, which include adjusting drill frequency, diversifying the skills targeted in drills, and making improvements in the communication of methods and answer keys.

2.4.5. Technical session 5 — Analytical methods for analysing radiological and nuclear evidence

Ms. Maria Wallenius (European Commission) reviewed the 30 year history of nuclear forensics at JRC-Karlsruhe, discussing the origin of nuclear forensics in the early 1990s, resulting from cases of smuggled radioactive material. She explained that while many early cases involved the loss and recovery of low enriched uranium (LEU) fuel pellets, JRC-Karlsruhe was also responsible for the analysis of material from cases involving high enriched uranium and/or plutonium. In addition to casework, JRC-Karlsruhe expanded its activities in nuclear forensics to include R&D activities, for example the development of $^{18}O/^{16}O$ measurements, metallic impurity concentration measurements, ^{234}U and ^{230}Th radiochronometry to better understand the origin of nuclear and other radioactive material out of regulatory control. In addition, she detailed ways in which JRC-Karlsruhe has partnered with the German Federal Criminal Police Office to identify and analyse traditional forensic evidence present alongside nuclear and radioactive material, including the installation and use of a dedicated glove box. Finally, Ms. Wallenius commemorated the passing of Lothar Koch, a co-developer of nuclear forensic science during its foundation in the 1990s, a co-founder of the Nuclear Forensics ITWG and a mentor to many scientists in the field of nuclear forensics.

Mr. Csaba Tóbi (Hungary) discussed recent developments in the use of positron annihilation spectroscopy (PAS) in nuclear forensics. This technique, commonly used to examine structural deficits in material, such as irradiated alloys, has not been used widely in the context of nuclear forensic examinations. He described experiments performed using PAS on a set of uranium ore concentrate and uranium oxide samples of known origin. Although these experiments were unable to readily distinguish between the material on the basis of origin, PAS was useful in distinguishing uranium oxide from uranium ore concentrate material, and would likely be able to differentiate other types of uranium compounds. He concluded by noting some possible applications of PAS to nuclear forensic analysis.

Mr. Manny Mathuthu (South Africa) presented an analysis of uranium ore concentrate for nuclear forensic fingerprinting using a scanning electron microscope. In this work, Mr. Mathuthu and colleagues conduct SEM and EDX analyses of uranium ore concentrates. Scans at ~100 000x magnification show detailed evidence of material clumping and reveal an average particle size range of 100–200 nanometres (nm). EDS spectra from the samples indicate that the chemical form of the material is UO_4. These analytical results confirm that the grain size and texture determined by SEM could serve as a nuclear forensic technique for discerning nuclear material provenance and process, particularly for material originating from different mines in South Africa.

Mr. Péter Völgyesi (Hungary) discussed a study on the use of X ray radiography in nuclear forensic examinations. This technique, a non-destructive analytical technique that can be applied to a variety of nuclear and other radioactive material, has not been widely used in nuclear forensics. The study made use of a portable X ray tube to perform radiography imaging of 11 sealed neutron sources. Samples were characterized using standard photographic methods before radiography analysis in order to identify key physical features. Seven samples contained ^{252}Cf, and four samples contained ^{244}Cm as neutron sources. Analyses were performed at the Budapest Neutron Centre and the data produced from these measurements demonstrated that it is possible to characterize the size, homogeneity and shape of various types of sealed neutron sources, without breaking the source seal. These properties can be interpreted as nuclear forensic signatures in the context of investigations into recovered radioactive sources.

Mr. Alexandru-Florin Berevoianu (Romania) presented the results of a nuclear forensic examination of 600 kilograms (kg) of uranium out of regulatory control. The examination was performed by the IFIN-HH, but also involved stakeholders from several other organizations in Romania, including the Ministry of National Defence and the General Police Inspectorate of Romania. In this case, uranium was discovered within an abandoned factory in Bucharest. The uranium material consisted of gamma radiography installations and containers for radioactive sources. The nuclear forensic team at the IFIN-HH used various techniques and instruments in the analysis of the material, including a portable high resolution gamma spectrometer and a portable X ray fluorescence spectrometer. Physical characterization measurements were performed, capturing key dimensional data on the material. In many cases, physical measurements were useful in determining the nature of this material. Isotopic composition analysis using gamma spectrometry revealed that the material was of a depleted isotopic composition, approximately 0.25% ^{235}U by weight. On completion of the two week analytical campaign, a technical report was drafted and provided to the investigative authority.

Mr. Jose Garcia Sainz (IAEA) provided perspective on how nuclear forensics could be further implemented in the context of the IAEA ITDB. The ITDB is a database used by the IAEA to track incidents of nuclear and other radioactive material out of regulatory control. He showed data describing the number and types of incidents that have occurred since 2012, noting that incidents of other radioactive material out of regulatory control have greatly exceeded the number of incidents involving nuclear material. Even in cases of the detection of nuclear material out of regulatory control, most incidents involved depleted uranium, and cases involving LEU were rare. In contrast, cases involving other radioactive material, such as ^{137}Cs, ^{90}Sr and other material with industrial or medical applications were more common, averaging about 100 per year between 2012–2020. He also noted that, given the lag time between the occurrence of incidents of nuclear or other radioactive material and the reporting of such incidents to the ITDB, the significantly lower number of incidents logged in the ITDB for the years 2021 and 2022 are almost certainly a function of this lag, and are not an indication of an actual decrease in the number of incidents.

2.4.6. Technical session 6 — Novel techniques applied to nuclear forensic examinations

Ms. Masturina Kracica (Australia) presented research on the development of methodologies to apply focused ion beam (FIB-SEM) combined with time of flight SIMS (ToF-SIMS) for use in nuclear forensics and nuclear safeguards. This hybrid technique has been used to analyse individual particles and bulk material at the micro-scale for high precision uranium isotopic analysis. Spatially resolved isotope ratio measurements are useful for assessing the micro-scale heterogeneity of a nuclear forensic sample, which could consist of uranium from a variety of sources, with characteristic isotope ratios that would become homogenized in a bulk measurement. In this study, FIB-SEM was combined with energy dispersive spectroscopy, as well as ToF-SIMS. Samples consisted of bulk, thin film and powder material. Samples were first imaged using SEM and characterized for chemical heterogeneity using energy dispersive spectroscopy. After identification of regions of interest for isotopic composition analysis, the ToF-SIMS was used to obtain high precision uranium isotope ratios on the micron and sub-micron scales. The study concluded that this technique could be useful for nuclear forensic examinations in the case of isotopic composition measurements in single particles containing uranium.

Mr. Gregory Brennecka (USA) described a collaboration between the USA, Australia and Argentina in the area of radiochronometry, called the Virtual Laboratory on Age-dating for Investigation Support (VLADIS). In this unique partnership mechanism, technical personnel from LLNL, LANL, ANSTO and the National Atomic Energy Commission of Argentina participated in a monthly round table conversation, conducted using teleconferencing software. Managed by the NSDD, the goal of VLADIS is to enable discussion between experienced and newer technical personnel on the topic of radiochronometry in nuclear forensics. The subject matter of the discussions varied on a monthly basis and included topics such as chemistry, mass spectrometry, data analysis and the interpretation of radiochronometry ages in the context of nuclear forensic examinations.

Mr. Klaus Mayer (European Commission) described possible applications of artificial intelligence in the evaluation of data in nuclear forensics. His presentation described the outcomes of a dedicated workshop that brought together experts in nuclear forensics and artificial intelligence to discuss how these two communities could collaborate in the development of machine learning and algorithmic approaches to data evaluation. Nuclear forensics involves the measurement of the physical, chemical, elemental and isotopic properties of nuclear or other radioactive material out of regulatory control. While these properties can be readily measured, interpretation of data in the context of nuclear security can be complex. Workshop participants identified several key challenges in the interpretation of nuclear forensic data, including small and/or incomplete datasets; inhomogeneous (aggregated) data; data sensitivity or transparency; transparency of conclusions; and confidence in the findings. Several pathways forward were identified, including promotion of the use of distributed learning models to enable the handling of sensitive data; establishment of an interface between subject matter experts and the selection of features and parameters by artificial intelligence in order to increase the transparency of conclusions; development of multi-block data analysis for comprehensive description of nuclear material using information from various measurement techniques; examination of the application of transfer learning; and investigation of the usefulness of synthetic data for the purpose of training and validation of artificial intelligence models.

Ms. Ruth Kips (USA) presented the results of collaborative research supported by the DOE and ISCN-JAEA, which focuses on the development and use of image analysis software in nuclear forensics. This study, performed by scientists at LLNL, LANL and ISCN, involved the collection and interpretation of SEM micrographs of particulate samples of nuclear material. While it is well understood that particle morphology is indicative of the nuclear material production process, further research is necessary to link specific particle morphologies to specific nuclear fuel cycle processes and nuclear material types. Moreover, while SEM is a useful tool for the collection of physical characterization data in particle samples, these data are most useful if they can be quantified rather than interpreted using qualitative observation. In this study, scientists from LANL, LLNL and ISCN used image analysis software to collect key particle data on a shared set of ten scanning electron micrographs of the particle standard reference material. The ISCN team used software that differed from that used by the LANL and LLNL teams. Preliminary results revealed that all three teams were able to generate similar quantitative results for the set of micrographs. The study concluded that, while examination of the standard reference material might represent an ideal case, it is possible for teams using different image analysis software to collect consistent particle data from the same samples.

Mr. Julien de Troullioud de Lanversin (USA) described challenges in the interpretation of nuclear forensic data in the context of the nuclear fuel cycle, as well as solutions to these problems through the use of reactor modelling codes. He discussed the development of the open source depletion software, OpeN IsotopiX, and its application to nuclear forensics. OpeN IsotopiX makes use of the OpenMC Monte Carlo particle transport code and applies this technique to reactor modelling. He explained that this mathematical approach can be used to simulate the nuclear depletion of a variety of nuclear and non-nuclear material, as well as the nuclear depletion of nuclear material with a complex irradiation history. He demonstrated how fluence estimation can be performed using select isotope ratios, and how individual nuclide production and destruction pathways can be determined. This approach, which is currently being used by several research institutes, has the potential to assist States in the interpretation of nuclear forensic data collected from the detection of nuclear or other radioactive material out of regulatory control.

2.4.7. Technical session 7 — Signature research on isotopic signatures and age dating

Mr. Eyal Elish (Israel) presented research on isotopic signatures and age dating, highlighting existing research that has been published on uranium and plutonium isotopic composition to distinguish samples of nuclear and other radioactive material, lead isotopic composition to differentiate ore bodies, and samarium isotopic composition as a novel signature. He then shifted the discussion to stable oxygen isotopes as potential markers of material provenance in nuclear forensics, followed by a brief review of radiochronometry ages. Mr. Elish closed by emphasizing the breadth of potential nuclear forensic signatures, and thus the need for international collaboration.

Mr. Zsolt Varga (European Commission) presented work on the measurement and validation of isotopic composition in inhomogeneous samples by ICP-MS. The work focused on the issue of inhomogeneity in nuclear and other radioactive samples. The research team used an intentional mixture of two well characterized reference materials with different uranium isotopic signatures, and then analysed the sample using ICP-MS, finding that the spatial resolution and instrument sensitivity were sufficient to identify the constituents and quantify their isotopic ratio. A future direction for this work is to extend the analysis beyond isotopic inhomogeneity and test the ability to measure elemental differences.

In his presentation, **Mr. Travis Tenner** (USA) described large geometry secondary ion mass spectrometry (LG-SIMS) oxygen isotope and impurity distribution characterization of uranium and oxygen bearing particles as signatures of process history. He described a potential process signature for uranium oxide material determined through the measurement of oxygen isotopes using LG-SIMS. The principle behind this method is that different synthesis processes for UO_2 will fractionate oxygen isotopes differently, yielding measurable differences in ^{18}O and ^{16}O. The research team analysed five certified reference materials and found that some of the material is resolvable and some oxygen isotope signatures are overlapping. Mr. Tenner also shared some promising advances in applying LG-SIMS analysis to determine potential isotopic signatures of contaminants, such as fluorine and chlorine. He concluded his presentation with a call for certified reference material of known provenance and process history for this type of work in order to promote use of LG-SIMS in determining potential process signatures.

In his presentation on the oxygen isotopes composition of uranium oxides in the nuclear fuel cycle as a new signature for process attribution, **Mr. Maor Assulin** (Israel) outlined the potential use of stable oxygen isotopes to determine the provenance of synthesized U_3O_8 from uranyl nitrate hydrate and UO_3. Experimental results indicate that the stable oxygen isotope signature in the synthesized U_3O_8 does not reflect the source material, nor the spiked acid. Furthermore, calcination time appeared to have little effect on the stable oxygen isotope signature. However, the rate at which the synthesized U_3O_8 cooled from its calcination temperature did yield a consistent ‘mass effect’, indicating that isotopic quenching during cooling is the primary determinant of the stable oxygen isotope signature.

To close out the session, **Ms. Theresa Kayzar-Boggs** (USA) presented work on cooperation to improve $^{231}Pa/^{235}U$ age dating measurements of uranium for nuclear forensics. This work represents a collaboration between LANL, LLNL and JRC-Karlsruhe. Ms. Kayzar-Boggs emphasized that there is presently no certified reference material for $^{231}Pa/^{235}U$ measurements; therefore, comparisons between laboratories and possible consensus provide a new and valuable baseline for the measurement technique. After outlining the two approaches to building protactinium standards, Ms. Kayzar-Boggs shared the project results, which showed good model age agreement between the three laboratories and a range of different uranium material, from LEU to HEU.

2.4.8. Technical session 8 — Laboratory capabilities

In her presentation on research, education and training activities at the Atomic and Nuclear Physics Laboratory of the Aristotle University of Thessaloniki, **Ms. Alexandra Ioannidou** (Greece) provided an overview of the capabilities of the Nuclear Physics Department at the university noting a strong collaboration with the Greek Atomic Energy Commission. She described how these capabilities might be used for nuclear forensics. While Greece lacks a dedicated nuclear forensic entity, Ms. Ioannidou enumerated the capabilities within the Radiation Physics Group at the laboratory, including in relation to gamma and alpha spectrometry, handheld detection equipment and expertise in detecting radioactive aerosols. She concluded her presentation with a summary of the courses offered at the university, along with a description of the facilities and workshops.

Ms. Haruetai Kasiwattanawut (Thailand) discussed Thailand’s efforts in establishing an International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 17025 accredited nuclear forensic laboratory. After providing a brief history of capacity building efforts carried out in Thailand in the field of nuclear forensics, Ms. Kasiwattanawut shared the details and benefits of establishing an accredited nuclear forensic laboratory in her country. She also shared some of the challenges that accompanied the accreditation, including garnering support from the policy level, designing and maintaining a document system, building technical competencies and maintaining the ISO system. Ms. Kasiwattanawut closed by sharing future plans for the laboratory to expand its scope of analysis.

Mr. Ike Dimayuga (Canada) shared information on the development of nuclear forensic capabilities at the Canadian Nuclear Laboratories (CNL), including the ongoing renovation and refurbishment of the site. The aim of the CNL is “providing solutions to challenges in energy, health, safety, security and the environment,” and nuclear forensics falls within safety and security missions. Mr. Dimayuga further described capabilities that include the measurement of uranium isotopic concentrations by thermal ionization mass spectrometry, gamma-gamma coincidence mass spectrometry and research on nuclear fuels. Specific nuclear forensic applications include the use of $^{235}U/^{238}U$ and $^{236}U/^{238}U$ to estimate the burnup of an irradiated sample and the use of ion chromatography to separate caesium and barium, relevant for ^{137}Cs radiochronometry.

Ms. Zeinab Hassan (IAEA) presented the Integrated Nuclear Security Support Plan (INSSP), a tool that can be used to strengthen nuclear forensics and radiological crime scene management in participating States. Her presentation included an overview of the INSSP Office, the countries they support and the Office’s functional areas. Ms. Hassan highlighted one of the INSSP objectives, which is to “identify radiological crime scene management and nuclear forensic needs and formalize arrangements”, and how it connects to the focus areas of the technical meeting. She also discussed regional versus national approaches to meeting Member State needs and optimizing training programmes. Ms. Hassan concluded the presentation by stressing that while the prioritization of needs is a Member State responsibility, the INSSP Office can help to translate these priorities into comprehensive capacity building.

Ms. Quillan Rose (IAEA) provided a review of nuclear security support centres and the role of nuclear forensics in scientific support, outlining more specifically the mission and objectives of the IAEA International Network for Nuclear Security Training and Support Centres (NSSC Network). The network, which currently has 66 members, encourages international cooperation and supports joint activities, identifies and documents best practices, and hosts meetings, workshops and technical exchange visits. Ms. Rose directed attendees to relevant guidance — IAEA Nuclear Security Series Nos. 20, Objective and Essential Elements of a State's Nuclear Security Regime [10], and 30-G, Sustaining a Nuclear Security Regime [11], respectively — and then outlined some of the core functions of the network, such as human resource development, technical support and scientific support.

2.4.9. Key themes emerging from the technical sessions

The presentations delivered in the technical sessions covered a wide array of topics, demonstrating the breadth of nuclear forensic examinations in the context of global nuclear security. The first four technical sessions situated nuclear forensics in the broader landscape of national legal and response frameworks and highlighted the importance of meaningful cooperation with crime scene management. Presenters noted in particular the need to consider sustainability in the development of nuclear forensic capabilities. Many presentations throughout the technical sessions included information on the sustainability of nuclear forensic capacities, which rely in part on networks dedicated to experts in nuclear forensics, NNFL maintenance, international collaboration and interlaboratory exercises.

The subsequent three technical sessions focused on the improvement of specialized nuclear forensic analytical techniques, such as SEM, X ray radiography, ToF-SIMS and other forms of mass spectrometry, radiochronometry and morphology studies. Presentations also showcased novel applications of techniques, such as mathematical simulations of reactor modelling and the use of artificial intelligence. Isotopic signatures were highlighted as key components for nuclear forensic investigations, including stable oxygen isotope ratios and spatial heterogeneity in actinide isotopic composition. A unifying theme that emerged from the technical presenters was highlighted in the final technical session, at which time presenters emphasized that creative collaboration can help to develop nuclear forensic capabilities. Universities and State atomic energy commissions, for example, could contribute to improving the quality of analyses through the accreditation of laboratories and the production of certified reference material for nuclear forensic analysis, as well as encouraging international cooperation in order to strengthen nuclear forensic and radiological crime scene management capabilities.

2.5. POSTER SESSIONS

Poster sessions held during the technical meeting focused on areas of active research for analytical techniques that can be used in nuclear forensic examinations, thereby demonstrating the present and future impacts of nuclear forensic science in the context of global nuclear security.

2.5.1. Poster session 1

Ms. Jovana Nikolov (Serbia) presented on the evaluation of different software codes in the analysis of gamma spectra for potential use in nuclear forensics. Her presentation provided the results of an exercise with colleagues from the Centre for Energy Research in Hungary, comparing the precision of the results generated using a gamma spectrometer with a coaxial detector (University of Novi Sad, Serbia) versus a planar detector (Hungary). Using samples containing uranium, from an ore deposit in eastern Serbia, both software enabled measurements and simulation methods for co-axial and planar detectors were shown to be appropriate for initial categorization of material with different geometries.

Ms. Naomi Dikeledi Mokhine (South Africa) provided a poster presentation summarizing work on the characterization of uranium bearing material using the high purity germanium (HPGe) gamma detector for nuclear forensic purposes. This work, conducted at the Centre for Applied Radiation Science and Technology at North-West University, uses HPGe gamma spectrometry to characterize samples of uranium ore and uranium ore concentrate from two uranium mines. The results show no correlation between the uranium ore and uranium ore concentrate in either uranium isotopic composition or in the total uranium content.

Mr. Krisztián Soós (Hungary) presented a poster on nuclear forensic investigation of sealed ^{244}Cm sources using non-destructive methods. As an emerging analyte of interest in nuclear forensics, ^{244}Cm can be used as an X ray or neutron source, as well as an alpha source, as is the case for the Mars exploration rovers. A team at the Centre for Energy Research completed the research through extensive characterization of eight ^{244}Cm sealed sources, using analysis by gamma spectrometry and age dating with ^{137}Cs and ^{132}I fission products, among other nuclear forensic techniques. Gamma spectrometry revealed the presence of ^{243}Cm and ^{245}Cm in the sealed ^{244}Cm source, as well as 40 fission products. The difference between the activity calculated from the measurements and the activity derived from the certificate was 22–24%, which could be a consequence of overlapping gamma peaks, poorly defined gamma emission probabilities or other factors.

Mr. Dmytro Kutnii (Ukraine) was unable to attend this year's technical meeting. In lieu of a presentation, he provided a poster abstract on an iterative method, combined with high resolution gamma spectrometry (HRGS) for physical characterization of uranium material in the framework of nuclear forensic investigations. The work is summarized as an exploration of algorithm based modelling and the interpretation of HRGS data from the sealed uranium samples of various shapes and physical properties. The iterative algorithm, aimed at determining a sample's uranium mass fraction and density, is applied to U_3O_8 powders, UO_2 powders, liquids and solid fuel elements. Results demonstrate an ability to distinguish between the samples on the basis of uranium mass fraction and density, as confirmed by independent analytical techniques.

2.5.2. Poster session 2

Mr. Tebogo Kupi (South Africa) presented results from recent work focusing on the use of rare earth element patterns to identify the origin of different types of uranium rich material as a potential nuclear forensic signature. Samples of uranium ore, collected from mines in South Africa and Namibia, were crushed, milled and dissolved before mass spectrometric analysis. The normalized lanthanide concentrations in the four samples generally displayed a negative slope of light rare earth elements and flat to downward sloping heavy rare earth elements. All samples showed a negative europium anomaly. Overall, the work demonstrates the consistency of ICP-MS measurements, but the similarities between the sample chemistry indicate that additional techniques and signatures would need to be employed to conduct a fruitful nuclear forensic investigation on the analysed samples.

Mr. Zsolt Varga (European Commission) discussed the preparation and validation of new plutonium material for use in radiochronometry measurements in nuclear forensics. The radiochronometry age (often interpreted as a material 'production date') is a key nuclear forensic signature in many investigations of nuclear or other radioactive material out of regulatory control, determined through measurement of the ratio of a parent nuclide to a daughter nuclide. A new set of plutonium age dating reference material was prepared in this study. Radiochronometry ages were determined for each reference material using the $^{234}U/^{238}Pu$, $^{235}U/^{239}Pu$, $^{236}U/^{240}Pu$, and $^{241}Am/^{241}Pu$ chronometers. Subsamples of each material were sent to independent laboratories for analysis, including nuclear forensics and safeguards laboratories in France, Sweden, the UK, the USA and at the IAEA Laboratories in Seibersdorf. Agreement between the radiochronometry ages produced through independent laboratory analysis provided confidence in age accuracy, strengthening the possibility of the use of the material as standard reference material for radiochronometry analysis in nuclear forensics.

Mr. Csaba Tóbi (Hungary) presented on Fourier transform Infrared spectroscopy (FTIR) can be used to assess its applicability to the types of uranium rich material that could be analysed in a nuclear forensic examination. While this technique has been applied in numerous previous nuclear forensic examinations, its full potential has not yet been explored. The study focused on the analysis of uranium ore concentrate samples of known origin using FTIR. Spectra were collected for each sample and compared in order to assess whether samples of different origins can be distinguished. The study demonstrated that FTIR data are useful for determining uranium ore concentrate origin through spectral comparison of samples of unknown origin to samples of known origin. In comparison to X ray diffraction spectroscopy, a technique capable of generating similar datasets, FTIR is a more cost effective and user friendly technique for the determination of the molecular structure of material.

Ms. Theresa Kayzar-Boggs (USA) discussed various projects in radiochronometry supported by the NSDD. She highlighted projects that focused on the development of the $^{230}Th/^{234}U$ and $^{231}Pa/^{235}U$ daughter and parent pairs for nuclear forensic analysis, as well as the infrequently used $^{226}Ra/^{230}Th$ and $^{227}Ac/^{231}Pa$ pairs. She described output from these projects, including the publication of manuscripts in peer reviewed scientific journals, the generation of model ages for certified reference material (and the development of new reference material), improvements in the use of alpha and gamma spectrometry in radiochronometry analysis, and the use of single collector instruments for radiochronometry. She also described some of the current challenges faced by nuclear forensic scientists in the application of radiochronometry, focusing on the age dating of uranium and plutonium from production cylinders.

2.5.3. Poster session 3

Mr. András Kovács (Hungary) presented results from a study that used optically stimulated luminescence and thermoluminescence dosimetry for nuclear forensic analysis. Optically stimulated luminescence and thermoluminescence dosimetry approaches have the potential to enable nuclear forensic scientists to calculate the gamma radiation dose received by non-nuclear material exposed to gamma emitting radionuclides in nuclear or other radioactive material out of regulatory control. While this technique has been well established for building material (e.g. bricks), there is significant potential for the application of this technique to modern electronic devices (e.g. mobile telephones, computers, digital watches and automobile parts). Various parts of electronic devices have variable absorbed dose responses to gamma radiation (e.g. the glass displays of mobile telephones). In this study, Monte Carlo simulations were tested in order to assess the application of retrospective dosimetry to various types of material. Experimental data were obtained following procedures developed by the Belgian Nuclear Research Centre, and simulation code was written using Geant4. The objective of this study was to determine if data simulated using Monte Carlo modelling agreed with data obtained experimentally.

Mr. Hudson Kalambuka Angeyo (Kenya) described applications of laser induced breakdown spectroscopy and confocal laser Raman spectromicroscopy in nuclear forensic analysis. In this study, laser induced breakdown spectroscopy was used to determine the concentration of a suite of trace elements of glassy material containing radionuclides. More specifically, the elements yttrium, rubidium, zirconium, strontium and tellurium were measured, as these elements commonly occur in post-irradiation uranium waste. One advantage of laser induced breakdown spectroscopy is the small sample size (i.e. ~1 mm) needed for analysis. In addition, this technique can be performed in such a manner as to ensure distance between the instrument operator and the material under analysis, which can be highly radioactive. The study examined major and trace element concentrations of uranium rich glasses of different size fractions. It was demonstrated that uranium concentration varied from 50 to 200 parts per billion, with uranium concentration higher in the larger size fractions.

Ms. Areerak Rueanngoen (Thailand) described the nuclear forensic capabilities of the Thailand Office of Atoms for Peace. The Office of Atoms for Peace has worked to establish a number of analytical capabilities and to establish a national nuclear forensics library. Ms. Rueanngoen noted the ongoing need to develop and expand capacity in nuclear forensic analysis, identified as a priority at the national level. This study describes the application of gamma spectrometry, X ray diffraction, SEM and ICP-MS for the analysis of reference material, including monazite ore containing significant amounts of radioactive impurities. Analysis of this reference material was performed in a manner similar to that which would be conducted in an actual nuclear forensic examination. The recently developed national nuclear forensics library will continue to be populated with data generated using the nuclear forensic analytical techniques available in Thailand.

Mr. Yoshiki Matsui (Japan) discussed the current status and future plans for the development of capacity in nuclear forensics at ISCN-JAEA. He described some of the nuclear forensic analytical capabilities at the ISCN, including the introduction of SEM and thermal ionization mass spectrometry. In addition, he described in detail procedures for the analysis of uranium isotopic composition and nuclear material production age with chemical separation and thermal ionization mass spectrometry. The ISCN has capabilities for the analysis of elemental composition, including X ray fluorescence spectrometry and ICP-MS. The use of these complementary techniques to meet the needs of the investigative authority was highlighted during the poster presentation. In addition, SEM is used by the ISCN for the collection of spatially resolved physical and chemical nuclear forensic data. The ISCN has also participated in the ITWG CMX.

Ms. Kalaya Changkreung (Thailand) described participation in virtual exercises in nuclear forensics during the COVID-19 pandemic. In an attempt to continue training and capacity building during a time when travel restrictions limited participation in training and exercises, and laboratory closures slowed down the progress of work, virtual exercises were further developed. In 2020–2021, Thailand was able to adapt to virtual engagement, particularly in the areas of developing nuclear forensic standard operating procedures and using software to interpret data collected from nuclear or other radioactive material out of regulatory control. The virtual exercises were adapted in a manner that could meet the practical needs of frontline officers in their response to the detection of nuclear or other radioactive material out of regulatory control. These virtual engagements made it possible for stakeholders to achieve near completion of the standard operating procedures.

2.5.4. Poster session 4

Ms. Doina Stanciu (Romania) presented on the implementation of traditional forensic methods and procedures within the IFIN-HH, outlining an experimental set-up for traditional forensics, which consisted of designing a glovebox that was built in-house. By controlling the chamber conditions, including temperature and humidity, scientists are able to optimize the conditions to achieve clear fingerprint readings. Clear and legible fingerprint analyses serve to support investigations by attributing seized material out of regulatory control to specific individuals.

Mr. Kirill Zhizhin (Russian Federation) shared work on the analysis of biological samples contaminated by nuclear or other radioactive material for forensic medical examination. In this work, eight portions of human lung were investigated for the presence of alpha emitting particles. These samples were first examined by alpha autoradiography. Then, on the basis of the results, SEM and EDX analyses were used to determine elemental composition and distinguish morphological characteristics. SIMS was also used to determine the isotopic composition of the samples. This work demonstrates the possibility of using complex analyses of biological samples in order to detect, localize and determine the characteristics of the particles contained in biological samples.

Ms. Mariia Ryabochenko (Russian Federation) presented on the application of alpha-autoradiography for the detection and identification of alpha emitting contamination in a nuclear forensic examination. In this work, the research team conducted a study to examine the influence of different etching conditions on the effectiveness of alpha autoradiography measurements. The experimenters varied the etching duration, the concentration of the etching acid and the temperature at which the etching took place, in order to determine an optimal set of parameters for preliminary evaluation of the type of alpha emitting isotopes present in the sample. The study is of particular interest for nuclear forensics because alpha autoradiography measurements allow parties to obtain some of the characteristics of the nuclear or other radioactive material before using more involved analytical methods.

Ms. Alina Nitrean (Moldova) presented on the joint examination of hair fragments, spores and uranium particles using SEM and EDX in the context of appropriately sequencing a collection of traditional and nuclear forensic evidence. The main finding from this project is that complex samples (i.e. samples with hair, pollen, and uranium microparticles) covered by a thin layer of conductive material (e.g. gold, carbon), can be investigated, including through morphological observations, to yield information about the elemental composition of traces of nuclear or other radioactive material. Therefore, it is a fitting way to gather information from forensic samples.

2.5.5. Key themes emerging from the poster sessions

The technical meeting's poster sessions focused on areas of active research for analytical techniques that can be used in nuclear forensic examinations, from the specialized uses of analytical equipment to the software used to interpret the resulting data. While the majority of the poster presentations addressed analytical techniques used in nuclear forensics, some presenters focused on the crucial theme of the relationship between nuclear and traditional forensics, noting the importance of collecting evidence and conducting analyses in a sequence that maximizes the amount of information gained and prevents irreparable damage to the evidence. As is the case for the topics presented during the technical sessions of the meeting, topics presented during the poster session demonstrated the impacts of nuclear forensic science in the context of global nuclear security.

2.6. INTERNATIONAL TECHNICAL WORKING GROUP — 25TH ANNIVERSARY

The technical meeting included a session dedicated to the 25th anniversary of the first meeting of the Nuclear Forensics ITWG. **Mr. Michael Curry** led off the discussion by describing the group as an informal association of official practitioners. With no regulatory or formal structure, the ITWG is able to contribute and accomplish more than would normally be possible by identifying and dispersing best practices in nuclear forensics. The ITWG conducts exercises (e.g. CMX, Galaxy Serpent), holds exercise review meetings, drafts after action reports and publishes outcomes in peer reviewed journals. Mr. Curry emphasized the group's development of ITWG guidelines, the conducting of professional development activities during annual meetings, and the sharing of experiences during annual meetings and in the ITWG Newsletter. Mr. Curry concluded his remarks by highlighting the ITWG work products, which include: (1) the Model Action Plan; (2) the NNFL Concept; and (3) the ITWG Newsletter.

Mr. Sidney Niemeyer provided remarks in a video created by the ITWG, in which he enumerated the sessions that were organized during the first gathering in 1995, including real world experiences in analysing seized material; on-site crime scene issues; techniques for analysing samples; the feasibility for forensic interpretations of technical analyses; and mechanisms for next steps and international cooperation. The ITWG was formed from this gathering, and the first meeting was scheduled for 1996 at JRC-Karlsruhe. This meeting was the beginning of a group that has been designated as 'formally informal', which it remains today, encouraging technical pursuits free of governmental approvals at every step. The group set up round robin exercises — now known as the CMX — which has become a core output of the ITWG. Mr. Niemeyer's video also included comments from former and current participants, for example **Tom Jourdan, Benjamin Garrett** and **Paul Thompson**. The ITWG longevity and continued independence is considered extraordinary, with the group serving as a catalyst for advancing the science and aiding capacity building activities. The group's future outlook highlights the importance of keeping the group technical, informal and proactive, since the ITWG ultimately exists to serve the nuclear forensic community.

In preparation for the ITWG 25th anniversary meeting, scheduled to take place in June 2022 in California, **Ms. Naomi Marks** conducted a poll among technical meeting attendees to assess their backgrounds and gain a sense of the ITWG events in which the attendees have participated. Among the technical meeting attendees at the session, the overall impression of the ITWG was one of collaboration and good practice, and the future activities most desired included tabletop exercises, case study webinars, professional development webinars, CMX events and field training. The desired meeting format for future ITWG events were ranked as: (1) in-person meetings; (2) hybrid meetings; (3) webinars; (4) online meetings; and (5) other activities (e.g. publishing of additional guidelines).

Mr. Klaus Mayer concluded the session with remarks that described the ITWG as "a miracle, a platform and a catalyst." He noted that the ITWG has persisted over three decades while being both informal and influential, which he characterized as extraordinary. Mr. Mayer explained that the ITWG platform facilitates communication and the development of good practices.

2.6.1. Key themes emerging from the International Technical Working Group — 25th anniversary session

This session provided a thoughtful retrospective on the first 25 years of the ITWG, inviting newly informed technical meeting attendees to learn more about the organization and its activities. The experience of the presenters, including those who spoke in Mr. Niemeyer's video intervention, spanned the lifetime of the group and emphasized the resiliency of this 'formally informal group', as well as the important contributions of the Model Action Plan, the NNFL concept and the ITWG Newsletter.

2.7. DEMONSTRATIONS AND INTERACTIVE EXERCISES

Over the course of the technical meeting, participants were introduced to a common scenario involving the smuggling of radioactive material. Participants were given the opportunity to observe and participate in the scenario through the use of video vignettes as well as real time demonstrations of radiological crime scene management and a mock trial. This section also includes a description of a case study, as well as of an ITWG mini exercise.

2.7.1. Part 1 of the scenario based interactive discussion: Rudas Cove

To introduce the video based scenario, **Mr. Frank Wong** (USA) facilitated a discussion involving the loss of radioactive material from a nuclear facility in a fictional city called 'Rudas Cove'. This fictitious scenario involves the theft of radioactive ^{137}Cs from a nuclear facility, which was 'discovered' out of regulatory control in the cellar of an apartment and in the rear storage compartment of a car. Using two video vignettes, the story was told from the perspective of the criminal organization responsible for the theft, with the 'narrator' being portrayed as the leader of the criminal organization. The scenario involved the narrator informing the man who committed the theft of ^{137}Cs, named 'Oskar,' about the many ways in which nuclear and traditional forensics can be used to link the thief to the stolen ^{137}Cs.

The first video vignette focused on exploiting material damage from radiation. The scenes in the video indicate that, although radioactive material is no longer on-site, law enforcement personnel know which car carried the radioactive material. With this specific information in relation to the car, law enforcement personnel are able to track the movement of both the car and the radioactive material. The video also illustrates that radiation creates measurable damage to material. Because smartphones are nearly always carried by individuals, evidence of a smartphone being exposed to radiation is a likely indicator that so too was its owner.

Following the first video, the audience was asked what additional information would be helpful to link Oskar to the crime scene where the ^{137}Cs was found. The two most frequent responses were: (1) evidence that Oskar was in the car that transported the radioactive material; and (2) surveillance video showing Oskar and the car at locations around Rudas Cove.

The second video vignette explored the significance of good practices at crime scenes, along with radiochronometry. Key themes illustrated in the second video include rules of evidence at the crime scene, which are similar with or without radioactivity, as well as the importance of following a nuclear forensic analytical plan. For radioactive material, age dating will determine the time since last purification. Along with other nuclear forensic signatures, age dating can help to determine if two seized materials are similar or different. If the material seized (e.g. from the crime scene and from the car) is similar, it could indicate that there is a common adversary.

Following the second video, the audience was polled regarding what additional measures would increase confidence in the technical findings. The top two responses were: (1) validated protocols for collecting and processing radioactive evidence; and (2) a validated nuclear forensic laboratory.

A concluding discussion explored the nuclear forensic interpretations of measurements that would be helpful for the investigation. The two most frequent responses from the audience were: (1) the potential similarities between the ^{137}Cs seized from the cellar and from the cargo mat of the car; and (2) the chain of custody of the seized ^{137}Cs.

2.7.2. Part 2 of the scenario

The second portion of the scenario was shared in the form of a demonstration, during which **Lt.-Col. Christian Kirchmair** (Austria) introduced the Republic of Austria's Federal Ministry of Interior's Special Intervention Unit Cobra. The Cobra Unit demonstrated its capabilities in relation to explosive ordinance devices (EOD) and CBRN explosive devices by following a fictitious video based scenario that demonstrates a backpack being abandoned by a suspect linked to the theft of radioactive material in the fictional city of Rudas Cove. The scenario stipulates that the backpack was discovered within the city's main railway station. Once the backpack was found by authorities, the station was evacuated, and EOD operatives were called to conduct an examination of the backpack in order to determine if it was explosively safe and free from radiation. The scenario then moved to an in-person, live demonstration. Operational personnel from the Cobra Unit performed a condensed demonstration of the assessment and safe recovery of the suspicious backpack. Given that scenario based intelligence and other information indicated that the suspect might have been developing a radiological dispersal device (RDD), EOD operatives made the decision to utilize a robotic uncrewed ground vehicle (UGV) to conduct the investigation. A radiation detector was mounted to the UGV, and as the robot approached the backpack, the radiation detector indicated the presence of low levels of radiation from the backpack. After consultation with scientific technical experts, a decision was made to further examine the backpack. The backpack was safely moved by the UGV to a portable remote X ray device, which then allowed Cobra Unit operators to fully investigate the backpack and determine that it was explosively safe, since neither the components of an RDD nor an improvised explosive device were observed. Finally, the backpack was transferred by the UGV to an appropriate container in preparation for its transfer to the laboratory for further nuclear and traditional forensic examinations.

2.7.3. Part 3 of the scenario

Mr. Kevin Kelly (IAEA) introduced personnel from two Hungarian entities, the Centre for Energy Research and the Criminal Technical Department of the Hungarian Police, who provided a demonstration of an investigation into, and recovery of evidence from, a radiological crime scene. These experienced investigators bring together technical and scientific expertise, combined with an extensive knowledge of law enforcement investigative operations.

Once again in the context of the continuing Rudas Cove scenario, the investigators demonstrated a concise yet thorough example of the safe and secure recovery of evidence from a radiological crime scene. The demonstration depicted the living area of the main suspect's apartment. The team's radiological coordinator (i.e. the assessor) made an initial assessment of the scene using a telescopic dose rate meter, which facilitated the entry of the team into the radiological crime scene. All staff engaged in the operation were wearing appropriate personal protective equipment. The team consisted of the radiological assessor, **Mr. Csaba Tóbi** (Hungary), the primary evidence collector (i.e. the scientist, detection expert), assistant evidence collector (i.e. law enforcement personnel) and the team coordinator and photographer, **Lt.-Col. Izabella Kakuja** (Hungary). When entering the scene, traditional investigations of evidence began with the oversight and support of the radiological assessor. Comprehensive images of the scene were taken, and areas indicating the presence of radioactive material (i.e. ^{137}Cs) were mapped. The investigative team then combined their skills to demonstrate the manner in which a mobile smartphone is collected using manipulators. The smartphone had been identified as a priority given the possibility that it contained information linking it to the suspect and to other perpetrators. The smartphone was double bagged, and the external bag was checked for contamination using swab sampling. The double bagged smartphone was then placed in a Faraday bag to inhibit the ability of the smartphone to receive calls, messages or data. The contamination, which was in a granular form, was sampled using a gun residue sampler and identified as ^{137}Cs. The demonstration team then conducted a cross-cordon transfer of evidence from the radiological crime scene to the forensic examination area. Once the smartphone had been transferred, it was placed in a portable glove bag for examination, and its contents were downloaded. The data content from the smartphone was shared in real time with the participants, allowing them to observe photographs, social media connections, text messages and location data. The smartphone was then prepared for further nuclear and traditional forensic examinations.

To conclude the demonstration, **Ms. Éva Széles** (IAEA) narrated a video dramatization of the forensic examination and conclusions for the participants. She presented a nuclear forensic examination of the evidence and provided a summary of the nuclear forensic findings. This examination confirmed that the smartphone had been exposed to radiation, a finding that could be relevant for the purpose of subsequent legal proceedings.

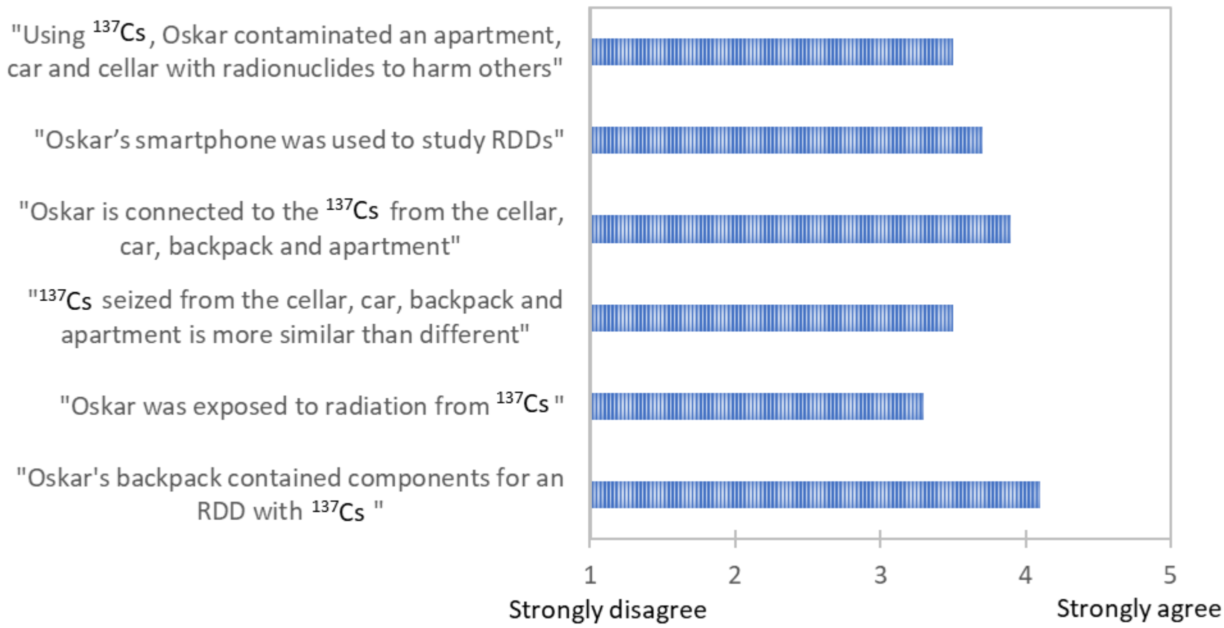
2.7.4. Part 4 of the scenario

The fourth part of the scenario took the form of a 'mock trial', involving the prosecution of Oskar for violating the legal statute of 'using radioactive material to harm people, plants, animals or the environment'. The technical meeting participants were asked to observe the mock trial, and then to answer a series of questions that were posed using interactive presentation software. Questions concerned the key technical conclusions supporting the prosecution and the defence of Oskar. On the basis of the arguments presented, the audience — serving as the jury — was anonymously polled to determine if Oskar was guilty or not guilty of violating the legal statute.

For this brief mock trial, the legal statute — a variation of a law from the Netherlands — stipulates that the prosecution needs to establish the intent to cause harm using the stolen ^{137}Cs material. In his role as a prosecutor, **Mr. Simon Minks** (Netherlands) noted that he is responsible for the integrity of the investigation in cooperation with the police. Mr. Minks explained that his role would also make him responsible for seeking both incriminating and exculpatory evidence, communicating effectively with experts while building a case and ensuring throughout the trial that human and civil rights laws are respected.

Thus far, the prosecution had been able to establish the contents of Oskar's smartphone, his connection to the ^{137}Cs, and some of his whereabouts. More information would assist the prosecution in determining that a terrorist group wanted to use the ^{137}Cs in the construction of a dirty bomb. Mr. Minks noted that, while it might seem obvious to the technical meeting participants that Oskar could be charged with a crime in relation to the use of ^{137}Cs, it might be more straightforward to convict Oskar on charges of simple possession of illicit material instead of an intent to cause harm.

Using the interactive presentation software, the audience was asked to: "Please assess the following statements supporting arguments that Oskar used radioactive material to cause harm" (see Fig. 2). A total of 56 responses were received from the audience.



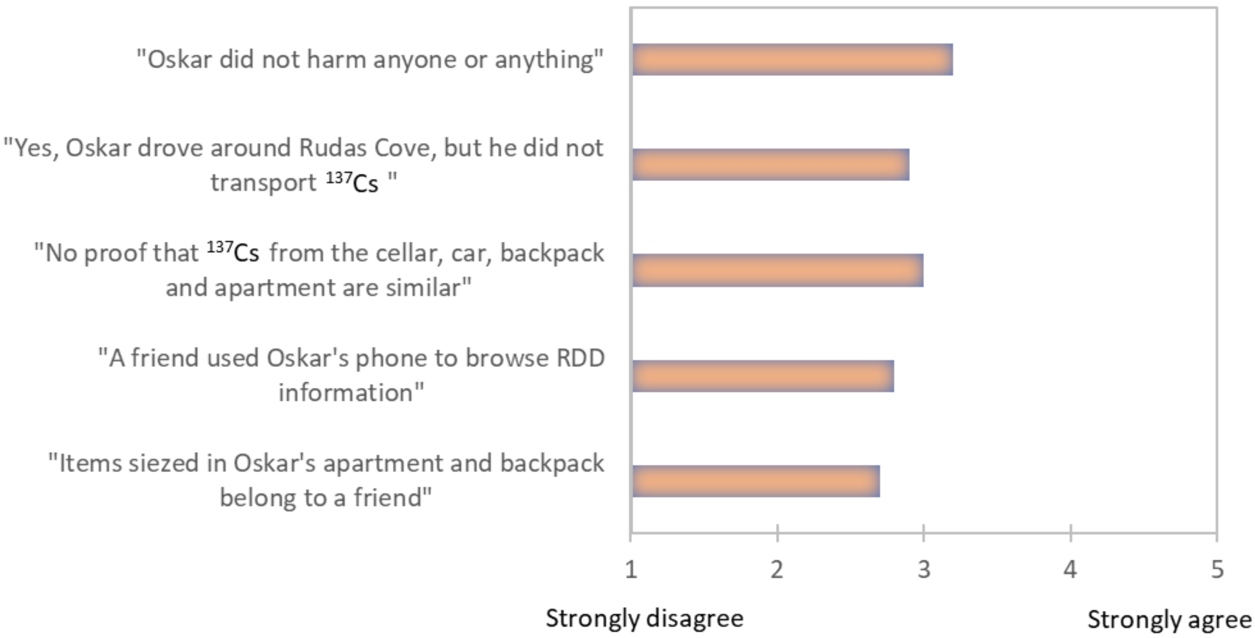
Note: Participant assessments of statements are averaged across the audience.

FIG. 2. Participant assessment of statements supporting the argument that Oskar used radioactive materials to cause harm.

Oskar was then given the opportunity to provide counter arguments, offering several rebuttals to the accusations, including raising doubts about the following:

- Whether the ^{137}Cs is a menace to anyone, since radioactive isotopes such as ^{40}K occur naturally in the human body;
- The comparison of the chemical and isotopic similarities between the ^{137}Cs found in the car, cellar and apartment;
- The meaningfulness of the similar ages of the ^{137}Cs found in the car, cellar and apartment, because significant amounts of ^{137}Cs are surely manufactured each year;
- The significance of an internet search for the term ‘RDD’ since the abbreviation can have other innocent meanings;
- The ownership of the smartphone in question, and the possibility of someone else having had the phone in his or her possession.

Following Oskar’s rebuttal, the second question from the interactive presentation software asked the audience to consider statements supporting the argument that he did not use radioactive material to cause harm. The results of this poll are shown in Fig. 3. A total of 56 responses were received from the audience.



Note: Participant assessments of statements are averaged across the audience.

FIG. 3. Participant assessment of statements supporting arguments that Oskar did not use radioactive material to cause harm.

Mr. Minks then discussed some considerations that a judge in this case might make, noting that the judge might conclude that there is not currently enough evidence to convict Oskar in the trial. He also added that a prosecutor might want to include a nuclear forensic expert in trial preparations, particularly in this case, because Oskar had been talking to the authorities and had provided statements that can be assessed by a subject matter expert.

The third interactive question asked audience members to: "Please rank the following key considerations in rendering a legal judgment" with 1st indicating the most importance and 6th indicating the least importance. With 57 people responding, the audience averaged rankings were as follows:

1st Oskar is connected to the ^{137}Cs in the cellar, car, basement and/or apartment;
2nd Oskar illegally obtained and possessed ^{137}Cs;
3rd Oskar tried to assemble an RDD;
4th Oskar has limited radioactive material handling expertise;
5th Oskar is just following orders;
6th Other considerations.

The majority of the audience concurred that the arguments presented did show that Oskar is connected to the ^{137}Cs in the cellar, car, and apartment, thereby revealing links between Oskar and the material, places and other items. Finally, the participants were asked to vote on the guilt or innocence of Oskar. The final vote result was 36 votes for 'guilty' and 26 votes for 'not guilty' (i.e. a total of 62 responses).

Mr. Minks noted the division among participants in assessing Oskar's guilt. He added that, while the scientific experts in the audience seemed clearly convinced that Oskar's story did not hold up, it is important to note that Oskar does not need to prove his innocence, only to demonstrate that he is not guilty. Mr. Minks suggested that it is unclear whether a jury would be able to assess the scientific evidence in the same manner as the scientific experts present in the audience at the technical meeting, or whether they would assign the evidence the same weight as the experts did during the mock trial.

2.8. CASE STUDIES

Two case studies were incorporated into the technical meeting programme to connect the themes of the meeting to real world cases involving nuclear or other radioactive material out of regulatory control.

2.8.1. Case Study: 'Joint response to ^{60}Co sealed sources outside of regulatory control'

Mr. Ed van Zalen (Netherlands) led the discussion with Mr. Jose Garcia Sainz (IAEA), Mr. Nico van Xanten (Netherlands), Mr. Jens-Tarek Eisheh, (Germany), Mr. Florian Baciu (IAEA) and Mr. Saiyadi Imam Sulaiman (Nigeria) concerning a set of incidents involving the discovery of capsules containing ^{60}Co out of regulatory control. These 25 gigabecquerel (GBq) capsules were found in scrap metal yards in both Germany and the Netherlands and were linked to shipments received from Nigeria. Mr. van Zalen explained that this is a first of its kind case, documented in a special April 2022 edition of the ITWG Newsletter[6].

Mr. van Xanten described the discovery of the sources. In November 2018, five sealed radioactive capsules were discovered in a Dutch scrapyard. The material was imported from Nigeria, but had not been detected by the radiation portal monitors at the Port of Rotterdam. The level of radioactivity exceeded the maximum set point of the radiation portal monitors and so the detection was missed. The maximum set point has since been adjusted. Mr. van Xanten noted that the company that discovered the material followed the correct procedures and reported the discovery to the regulatory authority. The radioactivity of the capsules was too high to have personnel handle them directly, and so appropriate military experts were tasked with conducting further categorization and characterization of the material from a safe distance. The purpose of the source was unknown. In early 2019, several more capsules were discovered in the Netherlands, leading to concerns about the total number of capsules that were outside of regulatory control. The incidents were promptly reported to the IAEA ITDB and an IAEA assistance mission took place.

Following Mr. van Xanten's description, **Mr. Eisheh** explained how the German authorities approached a similar case. He indicated that the discovery of capsules in Hamburg was promptly reported to the ITDB. Noting that the radioactive material found in Germany was very similar to that found in the Netherlands, the two States began to work together. Mr. Eisheh went on to say that the identification of a suitable laboratory was necessary, with two goals in mind. First, the States wanted to determine what type of sealed source or other radiation hazard they were facing, and second, the States wanted to obtain information about the current nuclear forensic capabilities in Germany and in the Netherlands.

Mr. Sulaiman outlined the actions taken by the Nigerian government in response to these capsules originating from Nigeria, first acknowledging the contact made by the Dutch nuclear regulatory authority to the Nigerian government and regulatory bodies. This initiation of contact prompted Nigeria to begin an investigation into the nature of the material. The Nigerian authorities had some information regarding the nature of nuclear and radioactive material smuggling in Nigeria. Noting the false address of the shipping company, Nigeria engaged the IAEA in a fact finding mission.

On the IAEA side, **Mr. Baciu** enumerated some of the additional steps that were taken in this case, including making preliminary details publicly available and then developing a plan with Germany, the Netherlands and Nigeria. Subsequent meetings tracked progress and examined the conclusions from the fact finding mission. **Mr. Garcia Sainz** described the involvement of the IAEA ITDB, noting the rarity of such occurrences, in

[6] The ITWG Newsletter can be consulted at: www.nf-itwg.org/newsletters/ITWG_Update_Special.pdf

which similar radioactive capsules were discovered in multiple sites over multiple months. It was decided that a comparison would be made between the radioactive capsules encountered and other entries in the ITDB. No other entries in the database appeared to match the orphan material found in Germany and the Netherlands. Mr. Garcia Sainz also mentioned the conversation between the ITDB and Nigeria, to make the latter aware of the incidents and establish a basis for collaboration. Mr. Garcia Sainz emphasized that the incidents were reported in a timely manner, which enabled the ITDB and other IAEA entities to respond quickly.

Audience questions prompted continued discussion among the panellists, first on the subject of the decision to conduct a nuclear forensic investigation. Mr. van Xanten explained that conducting external characterization and radiation measurements was feasible because of the Netherlands' existing laboratory capabilities and the high radioactivity of the samples. The samples were transferred to a national repository for storage in the case that additional analyses were needed. In this particular case, some of the categorization and characterization results from the German samples were useful in gaining more insight into the samples found in the Netherlands. An audience member asked about nuclear forensic signatures in the ITDB, and Mr. Garcia Sainz clarified that the purpose of the ITDB is not to track nuclear forensic signatures.

2.8.2. Case Study: 'Operation Vegas'

Lt.-Col. Christian Kirchmair (Austria) presented on the Republic of Austria's Federal Ministry of Interior's Special Intervention Unit Cobra, Directorate for Special Units, and its response to an alleged smuggling incident into Vienna. The material being smuggled was suspected of being radioactive (i.e. ^{235}U) and was believed to be smuggled by an organized criminal trafficking group. The case was part of an ongoing joint action by Austrian law enforcement, the General Police Inspectorate of The Republic of Moldova and the European Union Agency for Law Enforcement Cooperation (Europol), and it was designated 'Operation Vegas'. This cooperative initiative included transnational investigative measures to target a group of criminals who were attempting to sell a special container that allegedly held radioactive material (i.e. mainly uranium) for €3 million. During the comprehensive operation and subsequent intervention, three individuals were arrested in Vienna, one of whom had been previously convicted of a similar crime. Europol provided technical expert assistance at the scene of the intervention to support the analysis of the suspected nuclear or other radioactive material, and provided analytical and coordination support. The operational Austrian personnel had received specialist training in dealing with CBRN material before the intervention, part of which was provided through the General Directorate for Public Security, the Civil Protection Training School and the IAEA Collaboration Centre in Traiskirchen. Surveillance and seizure teams were equipped with tactical radioactivity measurement devices (i.e. electronic personal radiation dosimeters) during the intervention, detention and seizure operation. Cobra's rapid intervention team was able to facilitate a swift detention of the suspects and take control of the scene in what was a textbook operation. Subsequent forensic and laboratory investigations established that the material was inert and the sale of the material was, in fact, a scam. Trafficking in nuclear and other radioactive material is presently assessed as a potential risk to EU internal security. Despite the good work being carried out by law enforcement agencies, the possibility of the illegal movement of nuclear and other radioactive material remains present given the increased availability of material out of regulatory control from across the globe.

2.8.3. ITWG Mini exercise on national nuclear forensic libraries

Ms. Naomi Marks (USA) led a miniature, tabletop exercise on the subject of national nuclear forensics libraries (NNFLs). The IAEA Non-serial Publication, Development of a National Nuclear Forensics Library: A System for the Identification of Nuclear or Other Radioactive Material out of Regulatory Control [12], defines an NNFL as "a national system for the identification of nuclear and other radioactive materials found out of regulatory control". An NNFL could contain records that include physical, chemical and isotopic characteristics of typical material from many of the existing operational facilities. An NNFL also entails expertise so as to interpret records. In the scenario, participants return to the fictional Rudas Cove, where an NNFL has been developed to recognize nuclear and other radioactive material out of regulatory control. Authorities from Rudas Cove were notified of a possible suspicious facility, and a search of the facility resulted in the location of two jars. These jars had fingerprints on the labels and contained material that was visually consistent with natural uranium. A third, and possibly related, jar of radioactive material was identified at a street market, secured by a police officer and sent to the nuclear forensic laboratory. Participants were then asked to respond to questions by the investigative authority, with instructions to base their responses on the results of physical analyses, results of traditional forensics, trace element analysis of uranium ore concentrate material, and material contained at an NNFL from four facilities in Rudas Cove. In this mini exercise, the lead investigator has requested a comparison between the three jars (items 1, 2 and 3). Participants voted and discussed matters in relation to sample collection, the order of the analyses, subsampling within the jars, and uranium and trace isotopic composition. The participants were ultimately asked to rate how likely it was that items 1, 2 or 3 originated from Rudas Cove. This session, while short in duration, provided meeting participants the opportunity to think through a scenario in which an NNFL would be very useful for determining the likely origin of nuclear and other radioactive material out of regulatory control. Questions and comments throughout the presentation demonstrated thoughtful engagement on the part of the participants both in relation to the information provided and the fictional task at hand.

2.9. CLOSING SESSION

To conclude the four day meeting, **Mr. John Buchanan** (Interpol) offered some closing remarks, noting that the week's core takeaway was that nuclear forensics cannot be performed on an individual basis, but is rather a collaborative and international practice. He also highlighted the formidable progress that had been made in the field of nuclear forensics even during the disruptions associated with the COVID-19 pandemic. Mr. Buchanan acknowledged that the nuclear forensic community still has a long way to go, but said that it needs to be proud of its accomplishments to date.

Ms. Ruth Kips (USA) and **Mr. Frank Wong** (USA) then used a final interactive poll to gather some feedback from the audience on the meeting while information was fresh in the participants' minds. The poll indicated that participants found the sessions using the interactive presentation software the most useful, followed by radiological crime scene management demonstrations, oral presentations, moderated panel discussions and finally poster presentations. Participants shared that they viewed the hybrid meeting as a good and accessible format, but noted some technical difficulties, as well as the long days.

When asked to: "please rank the following themes that advance nuclear forensics from national foundations to global impact," the participants' aggregated rankings were as follows:

(1) Promote closer collaboration among law enforcement officials, regulators and nuclear forensic scientists;
(2) Increase opportunities for international collaboration;
(3) Advance the role of nuclear forensics in law enforcement investigations;
(4) Develop sustainable, indigenous nuclear forensic capabilities using nuclear forensic science and expertise;
(5) Promote nuclear forensics and radiological crime scene management to address future challenges.

When asked about new topics that could be covered in future technical meetings, participants suggested topics such as traditional forensics, infrastructure development, case studies, exercises and sample management. Participants were also asked to share some information about new ideas or topics that they had learned at this technical meeting that they will share with their colleagues at home. Many shared that they found the mock trial portion of the meeting the most novel and interesting, noting that it would be valuable to conduct additional mock trials at future meetings. Participants also highlighted the importance of NNFLs and national nuclear security response plans. Finally, the organizers and chairs of the technical meeting took the opportunity to thank everyone for their participation and support.

Mr. Daming Liu (IAEA), provided closing remarks for the technical meeting, emphasizing the importance of nuclear forensics in responding to nuclear and other radioactive material out of regulatory control, as well as the position of nuclear forensics within a state's nuclear security architecture. Mr. Liu thanked the Agency's international partners, the co-chairs of the meeting, Steering Committee members, and all of the meeting contributors, session chairs and participants. He noted the close connection between nuclear forensics and radiological crime scene management and the important role that both play in the IAEA Nuclear Security Plan 2022–2025. Mr. Liu also underlined that nuclear forensic science is a preventive measure that could ultimately strengthen globally interconnected nuclear security systems, adding that the relationship between nuclear forensics, traditional forensics and investigation support is critical and necessitates effective communication. Before the meeting's formal adjourning, **Ms. Éva Széles** (IAEA) closed by expressing thanks to all of the parties that helped make the meeting a success, including the Steering Committee and the Secretariat of the 2022 Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact (see Appendix).

3. KEY THEMES OF THE TECHNICAL MEETING

This Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact fulfilled a key task for radiological crime scene management and nuclear forensic science, as outlined in the IAEA Nuclear Security Plan 2022–2025 [1] (Section 58): Sharing experiences, lessons and good practices through technical meetings and workshops. In addition, since 2014, all IAEA General Conference resolutions[7] encourage States to share experiences, knowledge and good practices in nuclear forensics with due regard to the principle of protecting sensitive information. These resolutions also encourage States, if they have not yet done so, to consider establishing, where practical, national nuclear material databases or NNFLs. During this technical meeting, presentations and productive discussions enabled States to share advancements, challenges and successes in relation to radiological crime scene management and nuclear forensic science.

The following sections provide a brief review of how the technical meeting met its objective of promoting the key themes of capacity building, national responsibility, sustainability and cooperation, as well as the connection to radiological crime scene management.

3.1. CAPACITY BUILDING IN NUCLEAR FORENSICS

Capacity building in nuclear forensic science, from virtual engagements to new technologies, as well as to the development of future experts, was a common theme during the technical meeting.

3.1.1. Virtual initiatives for capacity building in nuclear forensics

Convening the IAEA 2022 Technical Meeting on Nuclear Forensics was met with collegiality among members of the international radiological crime scene management and nuclear forensic community, and an eagerness to connect both in person and virtually. The meeting demonstrated the unique and central role that the IAEA plays in providing a common gathering point for nuclear forensic practitioners to exchange ideas and experiences.

Presentations and discussions on capacity building in nuclear forensics highlighted the changes and improvements resulting from the global COVID-19 pandemic, as it affected all States and traditional methods

[7] IAEA General Conference Resolutions can be found at: www.iaea.org/gc-archives/type/resolutions

of engagement. Technical meeting participants agreed that initiatives to hold international events and engagements virtually, including the IAEA technical meeting, have been effective because they have the potential to increase the number and type of participants by lowering the monetary and logistical costs for participation. Further activities, such as the US ‘Spectral Flavor of the Month’ and the live streaming of field exercises by JRC-Karlsruhe, were developed to engage international partners during the pandemic. These activities were also effective at reaching a wider audience through a virtual format and will therefore continue in this format even as certain forms of traditional engagement resume. Virtual engagement methods also provided additional perspectives to existing nuclear forensic activities. Certain activities developed before the global pandemic also proved to be effective in virtual capacity building, for example the repeated implementation of the ITWG Galaxy Serpent exercise, which was first launched in 2013 as a first of a kind, virtual, web based international tabletop exercise focused on organizing data for an NNFL.

One example of an exercise developed during the pandemic was the hybrid field exercise (i.e. in-person and virtual) organized by JRC-Karlsruhe. This exercise, called EUSECTRA Remote Interactive eTraining (ERIeT), resulted in observations that differed in accordance with the participant groups, and so the observations from remote participants centred on interactions between scenario elements and broader themes, whereas in-person participants had a stronger sense of the technical details but fewer big picture observations. To maximize engagement and effectiveness, virtual capacity building activities can be designed to benefit from this variety of insights and perspectives.

The resiliency of well established personal networks allowed international nuclear forensic efforts to be sustained during the pandemic. However, developing a new network is more challenging for early career nuclear forensic practitioners when in-person interactions are limited or non-existent. For new experts in radiological crime scene management and nuclear forensics, the technical meeting noted that virtual engagements could serve as an effective first step to help new experts establish their networks, followed by in-person meetings and interactions to help build and expand these networks.

3.1.2. New technologies, R&D and signature research in nuclear forensics

Numerous presentations featured novel nuclear forensic signatures and addressing the potential use of artificial intelligence and machine learning to assist in nuclear forensics, for example in formulating conclusions involving powder morphology and textural analysis. Although in its early stages, the application of artificial intelligence and machine learning to nuclear forensics is being considered for its potential role in data processing and interpretation. Additional, novel nuclear forensic signature developments include spatially resolved measurements of composition and isotopic radiochronometry using laser ablation, as well as the determination of proliferation pathways using oxygen, hydrogen and other stable isotope ratios.

A common refrain in the technical meeting presentations was the need for new, better and more accessible certified reference material in nuclear forensics. This material is expensive to make, can be difficult to ship and receive, and is often unavailable. However, such material is of critical importance for measurement validation, interlaboratory calibration and equipment verification.

Several panel discussions and technical presentations during the technical meeting addressed the importance of the nexus between nuclear forensics and traditional forensics. Inclusion of a traditional forensic component in collaborative exercises and other events was encouraged since it could enable further fruitful interaction between nuclear forensic experts and law enforcement officials. Closer coordination between these communities would help to link forensic signature studies to relevant investigatory and prosecutorial needs. Several other sessions during the technical meeting discussed the need for more portable techniques in the field so as to better link radiological crime scene management to traditional and nuclear forensic examinations.

3.1.3. Newcomers in nuclear forensics

For States that are new to the field of nuclear forensics, it is important that the focus remain on using existing nuclear science and engineering expertise that is already present in the State, including robust, sustainable, cost-effective analytical equipment or facilities that can be housed in research institutes and universities. A recognized good practice involves assessing the capabilities already in place within a State, perhaps by pursuing an IAEA Expert Mission on radiological crime scene management and nuclear forensics, on the basis of the results of the IAEA questionnaire completed by the relevant competent authorities, as well as by reviewing Ref. [8], using tools, such as the GICNT Nuclear Forensics Self-Assessment Tool, and engaging in other practical exercises to identify capabilities and gaps. The development of capabilities could come from different areas of expertise, for example one State might begin from the radiochemistry side, while another State might start by developing nuclear forensics from the law enforcement side. Gamma spectrometry, which was featured in several presentations during the technical meeting, is likely the most available and widely applicable technique in nuclear forensics for material categorization and initial characterization. In addition to scientific expertise and instrumentation, it is key that States developing nuclear forensic capabilities collaborate with their law enforcement community to understand how nuclear forensics can be used in investigations and judicial proceedings.

3.2. NUCLEAR FORENSICS AS A NATIONAL RESPONSIBILITY

As a technical capability, nuclear forensic science supports a State's nuclear security regime. As discussed during the technical meeting, the integration of nuclear forensics in a State's national nuclear security response framework is most effective when communication among the different stakeholders, competent authorities and organizations (e.g. scientists, law enforcement, policymakers, regulators) is clear and collaborative. This communication leads to good practices when establishing the role of nuclear forensics in the context of investigating nuclear security events involving material out of regulatory control, and when enforcing the legal framework. The technical meeting emphasized that nuclear forensics encompasses more than just instrumentation or analytical measurements, but is a comprehensive plan established on the basis of legal proceedings 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 might include illicit trafficking incidents, the discovery of nuclear or other radioactive material out of regulatory control, or of material that has been improperly disposed of.

Nuclear forensic expertise and capabilities also have a role in assisting States to meet their obligations under international legal instruments. As discussed in one panel discussion, for States Parties to the Amendment to the Convention on the Physical Protection of Nuclear Material [4], obligations under Article 7 criminalize the unauthorized possession of nuclear material, and nuclear forensics can assist in providing the technical foundation to reveal links among people, places, events and material.

Also under the umbrella of a State's national responsibility is the establishment and maintenance of its NNFL, which is organized, maintained and controlled by the individual State and is commensurate with the size and complexity of the State's holdings of nuclear and other radioactive material. Presentations and discussions at the technical meeting revealed an increased interest in, and desire for, guidance on the development of NNFLs and on their ties to advanced methods of nuclear forensic science. An ongoing challenge that was discussed at the meeting is keeping the NNFL up to date, and populating it with material that is relevant to the nuclear forensic analysis of that particular State. The key capability that an NNFL provides a State is the ability to answer the question: "Does this material, which is out of regulatory control, belong to the State?"

3.3. SUSTAINABILITY AND COOPERATION IN NUCLEAR FORENSICS

Several presentations and discussions focused on efforts to develop a nuclear forensic workforce in recognition of the challenges associated with developing a sustainable national nuclear forensic capability. Presentations from several States described efforts to identify and train a next generation of nuclear forensic scientists. The presentations outlined significant efforts to attract younger, more diverse candidates with a better balance in terms of gender when recruiting nuclear forensic scientists, noting some success to date. However, presenters noted that more work needs to be done to make better use of talent pipelines, and concern was expressed about the relative attractiveness of a career in nuclear forensics as opposed to other competing areas, such as the development of small modular reactors for energy production. Universities were identified as a potential source of future nuclear forensic scientists, with many recent entries to the field emerging from academic studies in a wide variety of areas outside of nuclear science, including analytical chemistry, geology, computer science, material science, mathematics, national security studies and international relations. Several presenters also highlighted the essential role of mentorships in preparing the next generation of nuclear forensic scientists. As the current generation of nuclear forensic experts and practitioners continues to age, and will eventually retire, the critical role that senior scientists can play in mentoring the upcoming generation was recognized throughout the meeting.

Presenters, panellists and keynote speakers at the meeting highlighted the essential and central role of the IAEA to foster and encourage international cooperation in nuclear forensics. In fora such as these (e.g. the technical meetings), as well as through mechanisms such as the IAEA INSSP, various IAEA training courses and coordinated research programmes, the IAEA plays a critical role in enabling bilateral and multilateral cooperation in nuclear forensics. Several presentations in the technical sessions highlighted research conducted as IAEA Coordinated Research Projects and described how participation in research coordination meetings revealed research needs in key areas, which were then translated into individual projects in Member States. Panel discussions noted the success of the 2019 Technical Meeting on Nuclear Forensics, and many participants appreciated the increased role of radiological crime scene management in the technical meeting. They encouraged the IAEA to implement technical meetings on nuclear forensics and radiological crime scene management in the future, noting that it was possible to establish international cooperation and coordination at the bilateral and multilateral levels even through the hybrid meeting format.

Several presenters described ongoing bilateral cooperation in nuclear forensics, noting that cooperation between States with established and emerging nuclear forensic capabilities has proven to be beneficial for all parties. Several States currently developing their nuclear forensic capabilities outlined progress made since the previous technical meeting in 2019, in many cases noting an increased rate of advancement as a result of bilateral cooperation. They noted that States with advanced nuclear forensic capabilities have generally been eager to assist by sharing technical expertise, good practices and standard operating procedures in key nuclear forensic techniques, such as gamma spectrometry.

Participation in, and results from, internationally coordinated exercises in nuclear forensics were the subject of many presentations, during which presenters noted that these exercises are key tools to promote sustainability in nuclear forensics. The Nuclear Forensics ITWG CMX activities were highlighted in particular throughout the technical meeting, with many presenters discussing their State’s approach to analytical work. In several cases, presenters highlighted ways in which participation in the CMX improved their ability to perform nuclear forensic examinations on seized nuclear or other radioactive material. As many presenters described, the most recent exercise, CMX-7, was the first to incorporate ‘traditional’ forensics and radiological crime scene management alongside nuclear forensics by using an innovative approach called ‘crime scene in a box.’ This development in CMX was consistent with the need for better integration between law enforcement and nuclear forensic communities, which was the subject of one panel discussion, and it was a key theme throughout the technical meeting. Several panellists noted that the results of their participation in CMX-7 would likely be the subject of presentations at future IAEA technical meetings. Participation in the Galaxy Serpent exercise was also described in several presentations and panel discussions as a mechanism to better understand the implementation and use of national nuclear forensic libraries.

3.4. NUCLEAR FORENSICS AND RADIOLOGICAL CRIME SCENE MANAGEMENT

One of the main objectives of this technical meeting was to highlight the connection between radiological crime scene management and nuclear forensics, in particular by involving more participants from law enforcement and prosecution in the technical meeting. Rates of attendance of law enforcement and prosecutors at the technical meeting have in effect doubled from 2019 (~5%) to 2022 (~10%). Engaging stakeholders who are from all steps of the 'from crime scene to courtroom' timeline helped to highlight the importance of each stage of the process. Many presentations and panel discussions addressed developments in relation to the use of analytical techniques in the field (i.e. at the radiological crime scene), as well as the analysis of traditional forensic evidence contaminated with radionuclides. The live demonstrations showed how conventional crime scene management technology, from robotics and electronics to portable glove bags, can be used at a radiological crime scene, and are of particular benefit when data and images can be rapidly acquired without having personnel enter a radioactive area. Technical presentations and panel discussions also emphasized the importance of rules of evidence, the chain of custody, contamination control, and safe and secure transport.

On the basis of participant feedback, the mock trial interactive session was very well received, helping to illustrate the critical connections between radiological crime scene management and nuclear forensics. The open question posed during the mock trial was: 'What is the best way to ensure that high quality scientific data gets into the hands of the prosecutors who need it for the furtherance of investigations and legal proceedings?' Further use of the mock trial interactive session could help to identify and develop better practices in relation to the use of nuclear forensic findings by prosecutors. Prosecutors and technical experts alike will be able to understand how technical conclusions can help answer key questions, as well as the importance of having these key conclusions written in plain language for prosecutors to use in the courtroom.

Several topics were discussed that will help advance the state of the art in relation to the connection between radiological crime scene management and nuclear forensic science. Some of the key questions that arose during the technical meeting that will help shape this continued collaboration are:

(a) By using an agreed nuclear forensic analytical plan, measurements could deliver the types of data necessary, and their associated interpretations, to meet the relevant needs of prosecutors. What work does the nuclear forensic analytical community need to undertake to meet the needs of prosecutors?
(b) Prosecutors might not always be familiar with the new perspectives that nuclear forensic conclusions can provide. What technical results and interpretations can the nuclear forensic community produce that would be useful for prosecutors?
(c) Expensive, highly precise analytical instrumentation is in fact not always necessary for timely and useful nuclear forensic conclusions, which could be used to lead an investigation. Are nuclear forensic experts too focused on the wealth of technical information, foregoing the need for interpretation and contextual support?
(d) The role of interpretation, which not only concerns analytical results, is most important in discussions with law enforcement representatives and prosecutors. An improved ability to interpret the results generated in the nuclear forensic laboratory or at the radiological crime scene will benefit collaboration between law enforcement and nuclear forensic practitioners. How do nuclear forensic practitioners communicate conclusions from scientific measurements to a non-technical audience who could make decisions using these technical conclusions?

3.5. CONCLUSION

The Technical Meeting on Nuclear Forensics: From National Foundations to Global Impact focused on the key role of nuclear forensics in supporting investigations with strong connections to radiological crime scene management and judicial proceedings. The keynote remarks, the panel discussions and the case studies all highlighted the need to better link nuclear forensics to traditional forensics, to further develop investigatory capabilities through information exchanges between judicial authorities or other investigative bodies, and finally to foster strong links between the scientific, law enforcement and prosecution communities.

Appendix

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LIST OF ABBREVIATIONS

A/CPPNM	Amendment to the Convention on the Physical Protection of Nuclear Material
ANSTO	Australian Nuclear Science and Technology Organisation
CBRN	Chemical, biological, radiological and nuclear
CMX	Collaborative material exercise (ITWG)
EDX	Energy dispersive X ray (analysis)
EUROPOL	European Union Agency for Law Enforcement Cooperation
EUSECTRA	European Nuclear Security Training Centre
FIB-SEM	Focused ion beam scanning electron microscopy
GICNT	Global Initiative to Combat Nuclear Terrorism
HEU	High enriched uranium
HRGS	High resolution gamma spectrometry
ICP-MS	Inductively coupled plasma mass spectrometry
IFIN-HH	Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering (Romania)
INSSP	Integrated Nuclear Security Sustainability Plan
ISCN	Integrated Support Center for Nuclear Nonproliferation and Nuclear Security (Japan Atomic Energy Agency)
ITDB	IAEA Incident and Trafficking Database
ITWG	Nuclear Forensics International Technical Working Group
JAEA	Japan Atomic Energy Agency
JRC	Joint Research Centre (European Commission)
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
LEU	Low enriched uranium
NNFL	National nuclear forensics library
NSDD	Office of Nuclear Smuggling Detection and Deterrence (US Department of Energy)
NSS	Nuclear Security Summit
NSSC	Nuclear Security Support Centres (IAEA International Network for Nuclear Security Training and Support Centres)
NSTDC	Nuclear Security Training and Demonstration Centre (IAEA)
PAS	Positron annihilation spectroscopy
PNRI	Philippine Nuclear Research Institute
PPE	Personal protective equipment
RCSM	Radiological crime scene management
RDD	Radiation dispersal device
RNTPU	Radiological and Nuclear Terrorism Prevention Unit (Interpol)
SAT	Self-assessment tool (GICNT)
SEM	Scanning electron microscopy
SIMS	Secondary ion mass spectrometry
TL	Thermoluminescence dosimetry
ToF-SIMS	Time of flight secondary ion mass spectrometry
UNICRI	United Nations Interregional Crime and Justice Research Institute

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