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U.S. and Russian Collaboration in the Area of Nuclear Forensics

M. J. Kristo

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Michael J. Kristo, Ph.D.
Lawrence Livermore National Laboratory

Note to the Translator:

The term "nuclear forensics" does not seem to have a direct Russian equivalent. It is sometimes translated as "nuclear criminalistics" or "identification of nuclear material." Neither of these terms gives the precise meaning of the English term. Consequently, the definitions of the terms "nuclear forensics" and "nuclear attribution" provided in the second section of the paper should be tied to whatever Russian words are used in the rest of the paper to translate these terms

Introduction

Nuclear forensics has become increasingly important in the fight against illicit trafficking in nuclear and other radioactive materials [1]. The illicit trafficking of nuclear materials is, of course, an international problem; nuclear materials may be mined and milled in one country, manufactured in a second country, diverted at a third location, and detected at a fourth. There have been a number of articles in public policy journals in the past year that call for greater interaction between the U. S. and the rest of the world on the topic of nuclear forensics [2-6]. Some believe that such international cooperation would help provide a more certain capability to identify the source of the nuclear material used in a terrorist event. An improved international nuclear forensics capability would also be important as part of the IAEA verification toolkit, particularly linked to increased access provided by the additional protocol.

A recent study has found that, although international progress has been made in securing weapons-usable HEU and Pu, the effort is still insufficient [7]. They found that nuclear material, located in 40 countries, could be obtained by terrorists and criminals and used for a crude nuclear weapon. Through 2006, the IAEA Illicit Trafficking Database [8-9] had recorded a total of 607 confirmed events involving illegal possession, theft, or loss of nuclear and other radioactive materials. Although it is difficult to predict the future course of such illicit trafficking, increasingly such activities are viewed as significant threats that merit the development of special capabilities. As early as April, 1996, nuclear forensics was recognized at the G-8 Summit in Moscow as an important element of an illicit nuclear trafficking program. Given international events over the past several years, the value and need for nuclear forensics seems greater than ever.

Determining how and where legitimate control of nuclear material was lost and tracing the route of the material from diversion through interdiction are important goals for nuclear forensics and attribution. It is equally important to determine whether additional devices or materials that pose a threat to public safety are also available. Finding the answer to these questions depends on determining the source of the material and its method of production. Nuclear forensics analysis and interpretation provide essential insights into methods of production and sources of illicit radioactive materials. However, they are most powerful when combined with other sources of information, including intelligence and traditional detective work. The certainty of detection and punishment for those who remove nuclear materials from legitimate control provides the ultimate deterrent for such diversion and, ultimately, for the intended goal of such diversion, including nuclear terrorism or proliferation. Consequently, nuclear forensics is an integral part of "nuclear deterrence" in the 21st century.

Nuclear forensics will always be limited by the diagnostic information inherent in the interdicted material. Important markers for traditional forensics (fingerprints, stray material, etc.) can be eliminated or obscured, but many nuclear materials have inherent isotopic or chemical characteristics that serve as unequivocal markers of specific sources, production processes, or transit routes. The information needed for nuclear forensics goes beyond that collected for most commercial and international verification activities. Fortunately, the international nuclear engineering enterprise has a restricted number of conspicuous process steps that makes the interpretation process easier. Ultimately, though, it will always be difficult to distinguish between materials that reflect similar source or production histories, but are derived from disparate sites.

Due to the significant capital costs of the equipment and the specialized expertise of the personnel, work in the field of nuclear forensics has been restricted so far to a handful of national and international laboratories. There are a limited number of specialists who have experience working with interdicted nuclear materials and affiliated evidence. Therefore, a knowledge management system that utilizes information resources relevant to nuclear forensic and attribution signatures, processes, origins, and pathways, allowing subject matter experts to access the right information in order to interpret forensics data and draw appropriate conclusions, is essential. In order to determine the origin, point of diversion of the nuclear material, and those responsible for the unauthorized transfer, close relationships are required between governments who maintain inventories and data of fissile or other radioactive materials. Numerous databases exist in many countries and organizations that could be valuable for the future development and application of nuclear forensics. The contents of many of these databases may never be shared directly, but even the development of a worldwide, “distributed” database would greatly benefit international efforts. Only by sharing information about nuclear processes and materials can participants benefit from collective experience and knowledge to evaluate and prosecute nuclear trafficking cases. By encouraging the participation of those states where nuclear materials originate, the international community of nuclear forensics scientists gain important insights into the material required to deter future acts of nuclear smuggling.

Definitions

Historically, the terms “nuclear forensics” and “nuclear attribution” have been used interchangeably. Over the past few years, however, nuclear forensics experts have emphasized a distinction between the two terms.

Nuclear attribution is a process to identify the source of nuclear or other radioactive materials used in illegal activities, determine the point-of-origin and routes of transit involving such material, and ultimately contribute to the prosecution of those responsible. Nuclear attribution utilizes many inputs including: 1) results from nuclear forensic sample analyses; 2) understandings of radiochemical signatures and environmental signatures; 3) knowledge of the methods for production of nuclear materials and nuclear weapons development pathway; and 4) information from law enforcement and intelligence sources. Nuclear attribution is the integration of all relevant forms of information about a nuclear smuggling incident into data that can be readily analyzed and interpreted to form the basis of a confident response to the incident. The goal of the attribution process is to answer policy makers’ needs, requirements, and questions in their framework for a given incident.

Nuclear forensics is the analysis of intercepted illicit nuclear or radioactive materials and any associated materials to provide evidence for nuclear attribution. The goal of nuclear forensics analysis is to identify forensic indicators in interdicted nuclear and other radioactive samples or its surrounding environment, e.g., the container or transport vehicle. These indicators arise from known relationships between material characteristics and process history. Thus, nuclear forensics analysis includes the characterization of the material and correlation with production history.

Key U.S. and Russian, and international players

United States

There are several U. S. governmental departments and organizations with an interest in nuclear forensics. The National Technical Nuclear Forensics Center (NTNFC) has the central coordinating role for nuclear forensics in the U. S. government. In addition, they provide direct financial support to the material nuclear forensics research & development program. The NTNFC is a part of the Domestic Nuclear Detection Office (DNDO) in the Department of Homeland Security. The U. S. Department of State is the lead department for all interactions with foreign governments. There are a number of groups within the State Department with an interest in nuclear forensics, including the Nuclear Trafficking Response Group, the Nuclear Smuggling Outreach Initiative, the Preventing Nuclear Smuggling Program, the Office of Cooperative Threat Reduction, and the Global Initiative to Combat Nuclear Terrorism. The Defense Threat Reduction Agency (DTRA), a part of the Department of Defense, primarily funds activities in post-detonation nuclear forensics, that is, activities aimed at providing information for attribution of a detonated nuclear device (nuclear yield) or radiological dispersal device (RDD).

The National Nuclear Security Agency (NNSA) within the Department of Energy has several organizations interested in nuclear forensics:

- A new organization (NA-45) has been created with the responsibility for interdicted, but unexploded, nuclear devices. This mission includes not only ensuring that the device is rendered safe, but also for enabling the analysis of the device and its constituent materials necessary to determine its origin.
- In the Defense Nuclear Nonproliferation Program, different offices have funded research & development in some areas of nuclear forensics as part of their mission area in Dismantlement and Transparency (NA-241); international initiatives as part of their mission in Global Security Engagement & Cooperation (NA-242; and research & development activities with direct application to nuclear forensics (NA-22).

As experts in the technology of nuclear weapons and the civilian and military fuel cycles, the DOE national laboratories provide technical support for these U. S. government programs. Laboratories conducting research & development in the area of nuclear forensics include Lawrence Livermore National Laboratory (LLNL), Los Alamos

National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory (ANL), Savannah River National Laboratory (SRNL), Oak Ridge National Laboratory (ORNL), Sandia National Laboratory (SNL), and Idaho National Laboratory (INL).

Russia

In the Russian Federation, the Ministry of Foreign Affairs is responsible for interactions with foreign governments and is the counterpart to the U. S. Department of State. Delegations from the U. S. Department of State and the Russian Ministry of Foreign Affairs form the bilateral Counter Terrorism Working Group (CTWG).

RosAtom is the Federal Atomic Energy Agency and is responsible for the Russian nuclear enterprise. RosAtom provides policy guidance and control to the many Russian institutes and nuclear manufacturing sites.

The Bochvar Institute (VNIINM) has been designated as the leading institute for nuclear forensics in Russia. However, all of the Russian institutes and combines have expertise relevant to the nuclear forensics mission, including VNIITF, the Russian Institute of Experimental Physics (VNIIEF), the Angarsk Electrolytic Chemical Combine, the Mayak Production Association, Novosibirsk Chemical Concentrate, Elektrostal, etc.

European Union

The Institute for Transuranium Elements (ITU) is the nuclear forensics laboratory for the European Commission. Nevertheless, many of the countries of the European Community have their own national nuclear forensics laboratories. For example, the French nuclear forensic laboratory is the Commisariat à l'Énergie Atomique (CEA). The British nuclear forensics laboratory is part of the Atomic Weapons Establishment (AWE).

International technical working group (ITWG)

Many international nuclear forensics laboratories are cooperating to develop common technical strategies and knowledge bases that catalog nuclear processes for use in interpretation. The Nuclear Smuggling International Technical Working Group (ITWG) was formed in 1996 to foster international cooperation in combating illicit trafficking of nuclear materials [10]. More than 30 nations and organizations have participated in 11 international meetings and 2 round-robin analytical trials to-date. Technical priorities for the ITWG include the development of accepted protocols for the collection of evidence and laboratory investigations, the prioritization of techniques and methods for forensic analyses for nuclear and non nuclear samples, the organization of inter-laboratory forensic exercises, the development of forensic databases to assist in interpretation, and technical assistance for requesting countries.

The nuclear forensics laboratories participating in the ITWG are committed to undertaking the characterization of nuclear or other radioactive materials that have been confiscated and submitted to analysis by legal prosecution authorities. These laboratories have pledged to cooperate closely among themselves and with prosecuting authorities in order to facilitate the elucidation of illicit events involving nuclear and other radioactive materials. U. S. participation in the ITWG is sponsored by the U. S. State Department. Scientists from LLNL and Pacific Northwest National Laboratory (PNNL) have represented the United States from a scientific and technological perspective, while federal employees from the U. S. Department of State, Department of Homeland Security, and Department of Energy have represented U. S. policy interests over the years. Historically, the Russian Federation has been represented by attendees from RosAtom, although there was broader Russian participation at the ITWG Meeting in Obninsk in 1996. At ITWG-10 in Umea, Sweden, in 2007, two scientists from the Bochvar Institute accompanied the RosAtom representative and immediately became active participants in the meeting.

The International Atomic Energy Agency (IAEA) is an active participant in this group and serves as an intermediary between individual countries and the ITWG as necessary. The IAEA also keeps track of the nuclear smuggling problem through the International Trafficking Database (ITDB).

Areas of potential collaboration

Improved methods of analysis

Scientific analyses are the source of all nuclear forensic data. In general, improving methods of analysis is considered a purely scientific endeavor – with few, if any, security restrictions. Therefore, improving our methods of analysis might be an easy place to begin collaboration. However, precision and accuracy, incremental improvements in existing analytical techniques (Annex 2) are not likely to produce significant improvements in the nuclear forensic conclusions. Techniques that measure new properties of the material, which are independent from currently measured properties and strongly influenced by manufacturing process or location, would be particularly valuable.

Techniques that are significantly more sensitive or have significantly greater spatial resolution may also be valuable. Some analytical techniques currently require more sample material than is typically available; research and development to reduce the amount of material required would be important. So also, techniques that reduce the limit of detection or improve spatial resolution may reveal signatures that are hidden from us now. Previous efforts have moved signature discovery from the realm of bulk signatures (mm spatial scale) to micro-signatures (µm spatial scale); now, we need to move into the realm of nano-signatures (nm spatial scale).

Signature discovery

More important to the nuclear forensics enterprise than improved analytical techniques, though, is the discovery of new signatures – properties of the material that reveal the creator, how it was made, why it was made, and so on. Signatures provide meaning to the analytical data. However, for the same reason that signature discovery is more critical to nuclear forensics, it is also subject more concerns – proprietary concerns, security concerns, etc. We still may be able to make progress, despite these concerns, in two ways. First, we can start by working together to identify signatures for lower-threat nuclear materials, e.g., uranium ores, uranium ore concentrates (yellowcake), UF_6, or reactor fuel pellets. The material characteristics of these materials will not be as sensitive as higher-threat materials, such as HEU or Pu. As we build trust in our cooperative enterprise, we may be able to move towards these higher threat materials. Second, we can start developing generalized signatures, which cause less security concerns, and work towards more specific ones. For example, we may feel very comfortable in saying that "we find that the concentrations of Nb, Re, and W in reactor fuel pellets are very indicative of the fuel manufacturer," but not comfortable in saying that "this specific manufacturer always has between 30 and 40 ppmw of Nb in their material.

Knowledge management & analysis techniques

Knowledge management is one area that seems both important for the future of nuclear forensics and one that can be approached independently from concerns about data security. The fully populated nuclear forensics database is expected to be vast, particularly considering the broad range of nuclear materials to be covered and the extensive list of materials properties that may be important. We hope that the signatures discovery process will be able to reduce the number of properties required for adequate identification, but, until that proves to be the case, nuclear forensic data is likely to include as many properties as can be measured, given time and funding. In addition to raw nuclear forensics data, we also need the ability to store information about production processes and locations throughout the history of nuclear materials production.

Areas of productive collaboration might include methods for storing and managing all of this information, methods for analyzing these large amounts of multidimensional data in order to extract signatures using new, or at least newly applied, mathematical and statistical techniques. For example, at LLNL, we are exploring the use of principal components analysis (PCA) and partial least squares discriminant analysis (PLSDA) for reducing the dimensionality of the data to allow the user to visualize patterns and groupings in the data.

Confidence articulation

Ultimately, national decision makers will want clearly stated answers with an appropriate estimate of the reliability of that answer. Conclusions will, no doubt, be reached by the application of multiple signatures, each with its own estimate of reliability, to multiple material analyses, each with its own measured precision and accuracy. All of these uncertainties must be reduced to an overall level of confidence. This end goal will require the development and application of very sophisticated statistical methods. These research and development projects could, again, be conducted independently of tightly held data and signatures.

Future nuclear fuel cycles

The Global Nuclear Energy Partnership (GNEP), recently announced by DOE Secretary Bodman [11], poses significant new challenges with regard to securing, safeguarding, monitoring and tracking nuclear materials. In order to reduce the risk of nuclear proliferation, new technologies must be developed to reduce the risk that nuclear material can be diverted from its intended use. Regardless of the specific nature of the fuel cycle, nuclear forensics and attribution will play key roles to ensure the effectiveness of nonproliferation controls and to deter the likelihood of illicit activities. Ensuring that individuals or organizations participating in illicit trafficking are rapidly identified and apprehended following theft or diversion of nuclear material will continue to provide the best deterrent against unlawful activities. Key to establishing this deterrent is developing the ability to rapidly and accurately determine the identity, source and prior use history of any interdicted nuclear material.

Taggants offer one potentially effective means for positively identifying lost or stolen nuclear fuels. Taggants are materials that can be encoded with a unique signature and introduced into nuclear fuel during fuel fabrication. During a nuclear forensics investigation, the taggant signature can be recovered and the nuclear material identified through comparison with information stored in an appropriate database. Unlike serial numbers or barcodes, taggants can provide positive identification with only partial recovery, providing extreme resistance to any attempt to delete or alter them.

We have investigated the characteristics of a number of elements for use as potential taggants by modeling their behavior under irradiation using a standard reactor depletion code. We concentrated our efforts on elements that lie on either side of the fission yield curve (masses below ~70 or above ~170) to avoid overwhelming the taggant signature with the resulting build-up of fission products. In evaluating the results of these simulations, we looked for elements with multiple isotopes of low neutron absorption cross-sections. The ratios of these elements will not change very much during irradiation and can be used to encode information about the fuel. It would also be desirable to have a few isotopes that do change markedly under irradiation, since the relative abundance of these isotopes in irradiated fuel could serve as a measure of the neutron energy spectrum of the reactor and the fluence experience by the fuel.

Many questions regarding the behavior of the taggant during reprocessing and the effect of low levels (tens of ppmw) of the taggant on fuel fabrication and performance have yet to be addressed. These studies would be excellent areas for joint research and development activities.

International Leadership

In 2005 and 2006, Presidents Bush and Putin announced the Bratislava Initiatives and the Global Initiative to Combat Nuclear Terrorism [12-13], respectively. In the name of nuclear security cooperation and building capacity to combat terrorism, these initiatives call for enhancing ability to detect and suppress illicit trafficking and other illicit activities involving nuclear and radiological materials. Bi-lateral cooperation in this area would improve technical capabilities, by bringing together our countries excellent expertise in the area of nuclear forensics. Such cooperation would also set a significant precedent that might encourage greater international cooperation and sharing in this important nonproliferation and counterterrorism arena, particularly as the future international nuclear fuel cycle framework evolves.

Challenges to address

Security

The primary obstacle to greater nuclear forensics collaboration between the United States and the Russian Federation are security concerns regarding sharing of data and knowledge. To further complicate this challenge, the security restrictions placed on information sharing are not symmetrical. For example, the United States considers the isotopic composition of its HEU to be unclassified, while the Russian Federation considers it a state secret. On the other hand, the United States considers the mass of certain components of its nuclear weapons to be classified, while the Russian Federation does not.

Under some circumstances, the U.S. and the Russian Federation have shared classified or sensitive information with each other. For example, as part of the HEU Transparency Program, for example, some of the isotopic data that the Russians consider classified was shared with the U.S. Further consideration of ability to share information should balance the risk of disclosure with the benefit of disclosure. Balancing the potential benefits, for both Russia and the U.S., of a greatly improved nuclear forensics system, enabling rapid identification of nuclear material to improve counter-terrorism and non-proliferation capabilities, with national security concerns, should be explored more fully in the near future.

Funding

The U.S. has greatly increased the level of funding for nuclear forensics research and development since the terrorist attacks of September 11, 2001. Prior to this event, nuclear forensics was funded in a small way by far-sighted managers in the Department of Energy and by internal investments by a few national laboratories. However, despite this significant increase, the overall level of funding is small compared to the vastness of the technical issues that need addressing. It appears that nuclear forensics research & development performed in the Russian Federation, has been largely funded by the U.S.

Looking to the future, this area of cooperation seems to be ideally suited for new U.S.-Russian partnerships bilaterally and with third countries, should adequate national funding be obtained.

Legal & policy framework for cooperation

Much of our collaborative work in nuclear forensics has been conducted so far with reference to technical cooperation under the Nuclear Materials Protection, Control, and Accounting (MPC&A) Program. Although MPC&A is quite different from nuclear forensics, often the master task agreements negotiated under the MPC&A program are broad enough to accommodate nuclear forensic activities. Another umbrella agreement that has been used is the Warhead Safety and Security Exchange Agreements (WSSX). This agreement, in negotiation for renewal, provides for the exchange of unclassified technical information to enhance nuclear safety and security in both Russia and the United States.

The International Science and Technology Center (ISTC), established in 1992, is a program that the U.S. has used to fund cooperative research projects with Russian institutes. The ISTC coordinates the efforts of numerous governments, international organizations, and private sector industries, providing weapons scientists from Russia and the Commonwealth of Independent States new opportunities in international partnership. Through its political, legal, and financial frameworks, the ISTC contributes to Fundamental Research, International Programs and Innovation and Commercialization, by linking the demands of international markets with the exceptional pool of scientific talent available in Russian and CIS institutes.

There are several bilateral and international agreements that support the ultimate goal of nuclear forensics, i.e., the deterrence of nuclear smuggling and ultimately nuclear proliferation and terrorism. UN Security Council Resolution 1540 obligates states to take steps to prevent the spread of weapons of mass destruction and supporting technologies. The Global Initiative to Combat Nuclear Terrorism, originally signed by Presidents Bush and Putin in 2006, is broad enough coverage to support many collaborative activities in nuclear forensics and related activities. In the context of these agreements, new bilateral agreements between the U.S. and Russian may be needed to support the data exchange necessary for a completely successful collaboration in nuclear forensics.

Conclusions

There are many challenges that the U.S. and Russia can work to overcome in the coming years. Bilateral and multilateral cooperation is needed to advance an international forensics capability, needed to combat terrorism and stop nuclear weapons proliferation. Whether we pursue the establishment of an international sample archive or an actual sample library, with an internationally managed data and knowledge base, solutions will require a long time and many difficult negotiations to gain approval from all of the relevant countries. The U.S. and Russia can work together to initiate an approach that will advance international cooperation.

No collaboration in the area of nuclear forensics can be more important than that between the U.S. and Russia. We are the two largest nuclear weapons states - in size and capability. We have the largest stockpiles of weapons and material, the greatest number of experts in all facets of the nuclear enterprise, and both face the unacceptable risk of weapons-usable material falling into the wrong hands. With proper funding from both governments and with the appropriate bilateral agreements that allow appropriate data exchange while still protecting each country’s national security interests, we can make great progress together in improving our mutual nuclear forensics capabilities and strengthening the deterrence effect that it engenders and set an example for greater international cooperation.

Annex 1: LLNL collaborations with Russian and FSU Institutes

Analysis of interdicted HEU sample (LLNL/VNIINM)

Lawrence Livermore National Laboratory (LLNL) and the A.A. Bochvar All-Russian Scientific Research Institute for Inorganic Materials (VNIINM) collaborated on the analysis of a highly enriched uranium (HEU) sample from 2004-2006. Bulgarian customs officers interdicted the sample on May 29, 1999. The sample was transferred to LLNL for analysis on February 24, 2000. Extensive analysis of the sample was performed by LLNL, Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), and Savannah River National Laboratory (SRNL). These analyses confirmed that the material was HEU (~73% ^{235}U) from irradiated reactor fuel reprocessed around 1993. Nuclear and forensic signatures suggested an origin in Russia or the former Soviet Union. However, the U.S. lack of knowledge regarding exact Russian reactor characteristics prevented matching of U and Pu isotopics by reactor modeling. We were also unfamiliar with the process necessary to produce UO_2 with such particle sizes in the range of 0.1-1 μm.

The U.S.-Russian Counter Terrorism Working Group sought to establish a model for real-time interaction between U. S. national laboratories and Russian institutes on a real nuclear forensics case. They established an action item during their meeting on July 22-23, 2003, for the US to provide a portion of the "Bulgarian" HEU sample to a Russian institute for nuclear forensic analysis, including confirming laboratory analyses, reactor modeling, and material identification. This was considered to be a first step towards a new mechanism for sharing information and analysis relating to illicitly trafficked nuclear material. As part of this first step, the United States would provide funding for the Russian analysis of the sample and interpretation of the results.

U. S. Ambassador Black, in a letter to Foreign Minister Safonov, identified LLNL as the U. S. technical lead on the project. The Russian Foreign Ministry, in consultation with RosAtom, identified the Bochvar Institute as the Russian nuclear forensics laboratory for the project. Accordingly, LLNL negotiated a contract with the Bochvar Institute for the analysis and interpretation of a 0.59 gram aliquot of the original sample. Because of the small sample size, the Bochvar Institute was not able to perform a full radiochemical analysis, similar to that performed by LLNL. The contract between LLNL and VNIINM was signed on July 8, 2004, by both parties.

The analyses by the Bochvar Institute confirmed the findings of the U. S. national laboratories in all respects. In addition, the Russians found a minor, Al-containing phase in the sample that was not found in the US analyses. This phase could possibly be important in the attribution process. The Russians agreed with the general interpretations of the U. S. researchers: that the material was reprocessed HEU, that it was irradiated in a reactor to extremely high burn-up, and that it was probably being prepared for research actor fuel. However, they felt that this sample could have been produced by any nuclear state possessing the appropriate processing facilities and could not be attributed uniquely to Russia or the FSU.

Identifying characteristics of research reactor fuel (LLNL/VNIITF)

LLNL collaborated with the Federal State Unitary Enterprise-Russian Federal Nuclear Center – Academician Zababakhin Scientific Research Institute of Technical Physics (VNIITF), located in Snezhinsk, in the area of identifying characteristics of research reactor fuel. Research reactor fuel is one of the most significant nuclear threats because the material is frequently HEU and weapons-usable, and many research reactors are pulse reactors that experience very low burn-up. Consequently, the radioactivity in the fuel elements decays very quickly after use so the HEU parts can often be picked up by hand after only a few days without any adverse consequences. In addition, research reactors are frequently not protected at a level commensurate with the risk of diversion of a significant quantity of HEU .

VNIITF conducted detailed materials analyses of 3 research reactor fuels. They completed the analyses of 3 research reactor fuels. However, VNIITF had difficulty in obtaining export approval for the resulting data and eventually provided a report compiled from fuel design specifications and "binned" experimental data.

A current contract with VNIITF is exploring that possibility. This contract is funded by the U. S. National Technical Nuclear Forensics Center (NTNFC), an organization in the Domestic Nuclear Detection Office (DNDO) of the Department of Homeland Security. This FY07 contract consists of 3 tasks:

1. Development of data structures and format for a bilateral US/RF database for research reactor fuel. The key goal of this task is the test-loading of the database with data from 1 US and 1 RF research reactor.
2. Development of animations of 1 US and 1 Russian research reactor. It is felt that these animations are necessary to understand the mechanical structure of the research reactor fuel. Research reactor designs are highly individualized and typically consist of many fissile and non-fissile parts.
3. Development of methods for reconstructing the original geometry of research reactor parts from fragments of the original fuel.

We believe that the success of this project will lead to a larger effort that must necessarily involve the participation of multiple Russian institutes and US national laboratories. It will also require high-level approval from the U. S. and Russian governments in order to populate the database with information about some of the more sensitive reactor designs.

LLNL collaboration the Former Soviet Union (FSU)

Over the past fifty years, Central Asia has supplied the majority of uranium to the military and civilian nuclear fuel cycle of the Soviet Union and subsequently to the emerging republics of the former Soviet Union. Therefore, uranium ores, ore concentrates, and reactor fuels collected from Central Asia are critical elements for any sample reference library for nuclear forensics.

Over the past three years, the U.S. Department of Homeland Security has funded LLNL to collaborate with specialists with the Kazakhstan National Atomic Agency "Kazatomprom" to understand the characteristics of their uranium ore concentrate. In addition, the same project funds a project at the ULBA Metallurgical Plant, a subsidiary of Kazatomprom and one of the largest nuclear fuel manufacturers in the world, to conduct research on the identifying characteristics of low-enriched uranium oxide fuel pellets.

The Global Security Engagement and Cooperation (GSEC) Office of the U. S. National Nuclear Security Administration (NNSA) is supporting efforts to combat international nuclear smuggling through widening the knowledge base of uranium ore, uranium ore concentrates, and uranium tailings in Central Asia. In FY06, GSEC and LLNL teamed with technical experts from Vostokredmet in Tajikistan to sample and characterize uranium ore and uranium tailings from the country's Taboshar and Karta 1-9 uranium mining and milling sites. In FY07, GSEC and LLNL expanded this work to Kyrgyzstan, where we partner with the Ministry of Emergencies to sample and analyze uranium ores and uranium ore concentrates from the Kara Balta and Ming Kush sites. All of these samples have been, or will be, analyzed for major, minor, and trace elements, as well as the isotopic composition of the uranium.

Our initial results indicate the ability of the forensics signatures to differentiate unique sources of Central Asian uranium. For example, in Tajikistan, concentrations of the alkali elements (Na), alkaline earth elements (Ca), trace elements, such as Zn, Pb, V, and Ni, light rare earth elements (Ce, La, Nd) and U-234 isotopic content vary uniquely and distinguish individual sources of uranium. Based on these results, sampling is being expanded to include other sites in Kyrgyzstan and Uzbekistan. Together, this collaboration and these results are the foundation of a comprehensive nuclear forensics program in Central Asia.

Since 2002, LLNL has also partnered with the Uzbekhistan Institute of Nuclear Physics in Tashkent, with funding provided by the Institute for Science & Technology of the Ukraine (ISTCU), in a number of projects aimed at improving Uzbekhistan's capabilities to detect and analyze illicit nuclear material. For example, one project funded the deployment of a network for radiation monitors at the over 400 border checkpoints in Uzbekhistan for the detection of the movement of radioactive materials across their borders. Another project funded the development of a mobile laboratory to provide interdiction support to these checkpoints, as well as rapid response in the event of accidents releasing contamination. Still another project funded the development of modern nuclear forensic methods for detecting, determining, and origination of materials seized in illegal trafficking cases.

Annex 2: The nuclear forensic process [14]

Incident response

IAEA-TECDOC-1313 "Response to events involving the inadvertent movement or illicit trafficking of radioactive materials" provides detailed recommendations for the initial response to the interdiction of illicit nuclear material [15]. There are 3 key goals to any response:

- Minimization of any radiation hazards associated with the incident site
- Control of the nuclear or other radioactive material
- Preservation of both nuclear and associated traditional forensic evidence

From the standpoint of nuclear forensics, preservation of the evidence is vital. All activities should be sequenced to minimize destruction or contamination of the evidence. Furthermore, the collection of traditional forensics evidence should be performed in a manner that preserves the integrity of the nuclear forensics evidence and *vice versa*. It is essential that appropriate thought be given to the relative timing of the collection of radioactive evidence relative to traditional forensic evidence. However, the collection of forensic evidence must always be consistent with good radiological safety practice. Because of these detailed considerations, the incident investigators should be trained as, or accompanied by, a forensic scientist.

Due consideration must also be given to the legal ramifications of evidence collection. For example, the incident investigators must maintain appropriate chain-of-custody procedures during the evidence collection process. The nuclear forensic laboratory must then maintain the chain-of-custody paperwork that will tie the analytical results and conclusions to specific samples and crime scene locations.

Sampling & distribution

Evidence should be sent for analysis at a nuclear forensics laboratory, which is equipped to receive and process such samples. It is highly likely that the evidence is commingled, that is, that the traditional forensic evidence is contaminated with radioactive material and that the radioactive material contains some forensic evidence. Therefore, the receiving laboratory should be able to handle radioactive material and carefully separate the traditional forensic evidence from the radioactive material for later analysis by experts in each discipline. Nuclear forensics laboratories are outfitted and staffed to handle contaminated evidence and accommodate the requirements of both the traditional forensics and nuclear analysis.

The nuclear analysis laboratory should be an appropriately accredited and recognized facility with analytical procedures and staff qualifications that are documented and can withstand both scientific peer-review and legal scrutiny. The receiving laboratory must be able to receive and handle large amounts of nuclear materials, yet still be able to analyze trace levels of the material constituents and environmental types of materials. It should be fully qualified to current standards in environmental, safety, and health protocols, hazardous waste disposal procedures, and hazardous materials handling and storage. The nuclear analysis laboratory should be intimately familiar with the requirements of a legal investigation, including the ability to perpetuate the sample chain-of-custody that began in the field.

Analysis of material

The forensic scientists will first develop an initial experimental plan, including methods for preventing contamination or cross-contamination of the evidence. Because of the dynamic nature of the forensics process, the scientists will modify the experimental plan as new information about the sample or the investigation is obtained. Since nuclear material is often not homogeneous, a single bulk analysis may not be appropriate to fully categorize, characterize, or attribute the sample. Good sampling techniques will be required to adequately characterize the radioactive evidence. Particles of stray minerals, unique industrial materials, pollen, spores, etc., may become associated with the package along the trafficking route. The unique signatures of such particles may provide strong evidence of the route taken by the package. In addition, when the amount of material being sampled is small, the experimental plan must allocate the limited amount of sample. In this case, it is important that all non-destructive analyses be performed first and that trace and microanalytical techniques be favored over techniques that require large amounts of material.

Nuclear material analysis

Nuclear forensics involves an iterative approach, in which the results from one analysis are used to guide the selection of subsequent analyses. In this way, radioactive materials analysis applied to nuclear forensics proceeds in a manner not unlike that of traditional forensic analysis. It is important to emphasize that all sampling and analysis must be performed with due regard for preservation of evidence and perpetuation of the chain-of-custody. The sampling process can equally extract and obliterate evidence. Many of the analytical tools used in radioactive materials analysis are destructive, that is, they consume some amount of sample during analysis. Therefore, the proper selection and sequencing of analyses is critical.

The nuclear forensic scientist has a wide array of analytical tools to use for detecting signatures in radioactive material. These individual techniques can be sorted into three broad categories: bulk analysis tools, imaging tools, and microanalysis tools. *Bulk analysis* tools allow the forensic scientist to characterize the elemental and isotopic composition of the radioactive material as a whole. In some cases, bulk analysis is necessary to have sufficient material to adequately detect and quantify trace constituents. *Imaging analysis* tools provide high magnification images or maps of the material and can confirm sample homogeneity or heterogeneity. Imaging will also capture the spatial and textural heterogeneities vital to fully characterize a sample. If imaging analysis confirms that the sample is heterogeneous, then *microanalysis* tools can quantitatively or semi-quantitatively characterize the individual constituents of the bulk material. The category of microanalysis tools also includes surface analysis tools, which can detect trace surface contaminants or measure the composition of thin layers or coatings, either of which could be import for interpretation.

The Nuclear Smuggling International Technical Working Group (ITWG) has achieved general consensus on the proper sequencing of techniques so as to provide the most valuable information as early as possible in the interpretation process (see Table 1). This consensus was achieved through discussion and consultation at regular meetings, as well as from experience developed from two round robin analyses.

Table 1. Sequence for Techniques/Methods*

Techniques/Methods	24-Hour	1-Week	2-Month
Radiological	Estimated total activity Dose Rate (α, γ, n) Surface Contamination		
Physical Characterization	Visual Inspection Radiography Photography Weight Dimension Optical Microscopy Density	SEM (EDX) XRD	TEM (EDX)
Traditional Forensic Analysis	Fingerprints, Environmentally sensitive samples	Fibers	
Isotope Analysis	γ-spectroscopy α-spectroscopy	Mass spectrometry (SIMS, TIMS, MC-ICP-MS)	Radiochemical separations
Elemental/Chemical		ICP-MS XRF Assay (titration, IDMS)	GC/MS

***All times above refer to time after receipt of sample(s) at the nuclear forensic laboratory.**

Traditional forensic analysis

Traditional forensic analysis, like radioactive materials analysis, is an iterative process, in which the results from one analysis are used to guide the selection of subsequent analyses. The forensic analyst must carefully examine all of the items seized at the incident site in order to uncover as much information as possible. Unlikely and apparently unrelated evidence often are key to the successful prosecution of a case. Once again, all sampling and analysis must be performed with due regard for preservation of evidence and perpetuation of the chain-of-custody. The collection of traditional forensic evidence on radioactively contaminated materials must also be performed in a manner consistent with good radiological safety practice.

The variety of traditional forensic evidence, as well as the methods of collection and evaluation, is almost limitless. For example, evidence such as tissue, hair, fingerprints, and shoeprints can often associate a specific individual with a specific place or object. The analysis of fibers, pollen, or chemical substances found at the incident scene can provide information about motives or transportation routes. Documentary evidence provides useful information not only in the content of the communication itself, but also in the incidental details of its creation (paper, ink, film type, extraneous noises, and accents). Similar to collection of radioactive evidence, the international community has agreed upon a sequence for traditional evidence collection. In Table 1, the collection of fingerprint and environmentally sensitive samples, e.g., gunshot or high explosive residues or DNA bearing samples, must occur within the first 24 hours after sample receipt. Fingerprint evidence should be collected by non-destructive means first (laser and photographic methods), then by dusting and lifting. The chemical analysis of other evidence by techniques, such as gas chromatography/mass spectrometry (GC/MS), may occur up to two months after the recovery of evidence.

Nuclear interpretation

Case development is very much a deductive process (see Figure 1). The nuclear forensic expert develops a hypothesis or set of hypotheses based upon the results so far. This hypothesis suggests additional signatures, which either might or must be present if the hypothesis is true. The expert then devises tests to verify the presence or absence of the signatures. Access to other experts around the world, to forensics knowledge bases, and to archived sample libraries are important tools that allow the nuclear forensics expert to formulate the hypothesis and the method to test it. If these tests show that the signature is absent, then the nuclear forensic scientist must abandon or adjust his hypothesis to fit the new results. If the tests show that the signature is present, then either a unique interpretation has been achieved or additional tests must be devised to exclude the other possible scenarios. At the beginning of the nuclear forensics process, the results from the radioactive materials analysis and traditional forensic analysis will most likely be consistent with many scenarios. As the process continues and new results prove inconsistent with those scenarios, certain scenarios are excluded. In the optimum case, only a single scenario will eventually prove consistent with all results.

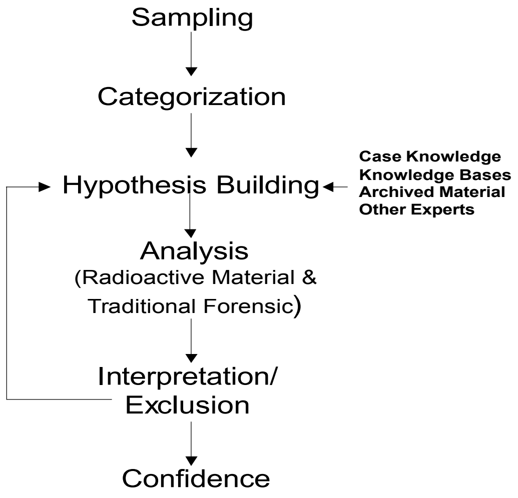

Figure 1. Flow Chart of Interpretation Process

Analytical results should be interpreted by experts representing a spectrum of all forensic specialties. Nuclear forensic experts use both an empirical approach, through the previous analysis of nuclear and other radioactive materials, and a modeling approach, based upon the chemistry and physics of nuclear processes to predict relevant signatures from those processes. They also use their knowledge of analytical science to select the appropriate methods to verify the presence or absence of predicted signatures. It is important to remember that all interpretations must follow the rules of evidence appropriate to the jurisdiction of the case.

Relevant signatures

Signatures are the characteristics of a given nuclear or other radioactive material that enable one to distinguish that material from other materials. These signatures enable one to identify the processes that created the material, aspects of the subsequent history of the material, and potentially the specific locales in the history of the material. Forensic scientists classify signatures as either *comparative* or *predictive*. Comparative signatures allow the comparison of an unknown or "questioned" sample versus a set of known samples. Predictive signatures allow deductions about the source, purpose, manufacturing method, etc., of a sample from basic chemical and physical principles – without reference to a known sample.

Signatures include *physical*, *chemical*, *elemental*, and *isotopic* characteristics of the material. *Physical* characteristics of the material include the texture, size, and shape of solid objects and the particle size distribution of powder samples. For example, the dimensions of a fresh nuclear fuel pellet are often unique to a given manufacturer. The particle size distribution of uranium oxide powder can provide evidence about the uranium conversion process. Even the morphology of the particles themselves, including such anomalies as inclusions, can be indicative of the manufacturing process. *Chemical* characteristics of the material include the exact chemical composition of the material or the association of unique molecular components. For example, uranium oxide can be found in many different forms, e.g., UO_2, U_3O_8, or UO_3, each of which can be found at various points in the uranium fuel cycle. *Elemental* signatures of the material include the determination of major, minor, and trace elements in the material. Major elements, of course, help define the identity of the nuclear material, but minor elements, such as erbium or gadolinium that serve as burnable poisons, help define its function. Trace elements can also prove to be indicative of a process. *Isotopic* signatures of the material include the detection of fission or neutron-capture products, which are indisputable evidence that the material has been in a nuclear reactor and serve as a fingerprint for the type and operating conditions of a given reactor. Other isotopes are decay products from radioactive "parent" isotopes in the material. For example, ^{230}Th is a decay product of ^{234}U and ^{235}U is a decay product of ^{239}Pu. Because radioactive isotopes decay at a rate determined by the amount of the isotope in the material and the half-life of the parent isotope, one can use the relative amounts of decay products and parent isotopes to determine the "age" of the material (time since the parent isotope was last chemically separated from its decay products).

Access to knowledge from the broadest collection of experts increases the chances of a unique and successful interpretation of the data. Sharing of information between international nuclear forensics laboratories leverages the extensive experience and newly developed capabilities of each laboratory to derive new and valuable information from the material analysis. The participation of other nuclear forensics laboratories also allows for a peer review of the nuclear interpretation process, increasing confidence in the validity and impartiality of the interpretation effort. As already noted, international collaboration is essential to the worldwide problem of control of nuclear material. By their very nature, nuclear incidents can be dynamic and itinerant, with nuclear material sourced in one site and transported to another. The ability to share some details of specific incidents, unique analytical capabilities, and knowledge databases is important for countering the nuclear threat.

It is important to remember that different signatures exist for different materials at different points in the nuclear fuel cycle (see Figure 2). Each processing step has the ability to both create new signatures in the product material and destroy signatures present in the incoming feed material. Currently, no signature has been identified that persists throughout the nuclear fuel cycle. Therefore, any signature must be referenced to a specific material and point in the fuel cycle.

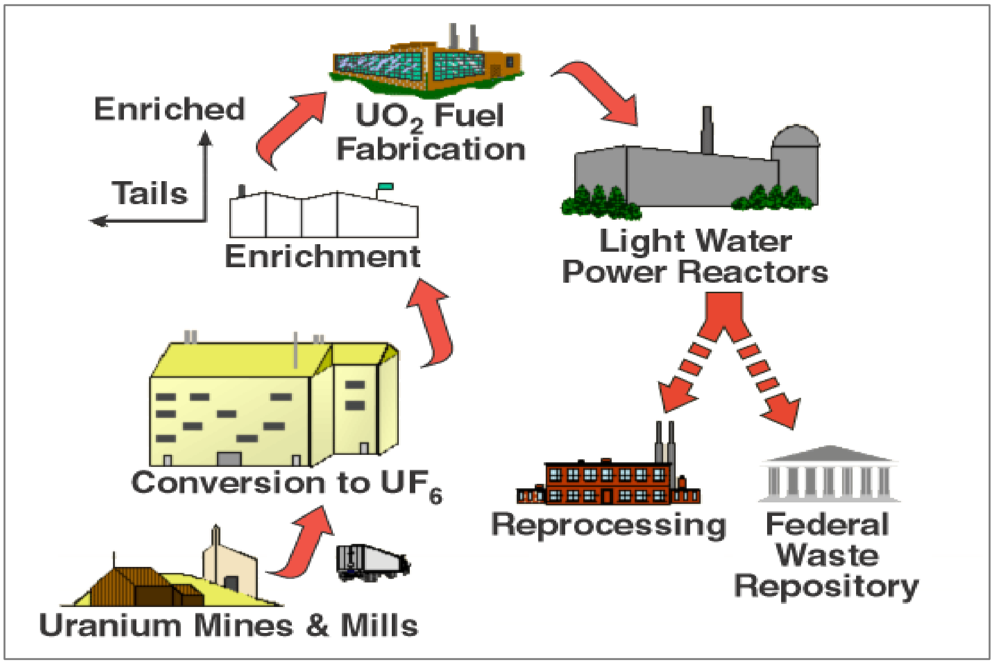

Figure 2. The Nuclear Fuel Cycle

Knowledge Bases

Extensive knowledge bases of nuclear processes and nuclear forensic data are necessary for effective interpretation of the laboratory results and their successful application to existing information on the sources, methods, and origin of nuclear materials throughout the world. This ability to compare signatures with existing knowledge and data is at the heart of the interpretation process. These knowledge bases are presently maintained by a variety of international, national, and non-governmental entities.

There are current efforts to develop and organize knowledge bases that catalogue nuclear processes for use in nuclear forensics investigations. Many of the basic nuclear processes are documented in textbooks, reports, and papers in the open literature. These documents can be found in technical libraries, as well as the World Wide Web. The IAEA web-site (http://www.iaea.org/), for example, has a number of databases that document publicly available information about nuclear facilities around the world. Proprietary or classified processes, though, may only be documented in the so-called "closed" literature. Companies are often willing to share proprietary information with national nuclear forensics laboratories after the execution of an appropriate non-disclosure agreement. In addition, national laboratories are usually able to access the classified literature of their own country, but obviously not those of other countries. This makes international cooperation between nuclear forensics laboratories of vital importance to solving certain cases.

In some cases, such as the combined Institute for Transuranium Elements (ITU)-Bochvar Institute database for commercial nuclear fuel [16-18], these knowledge bases contain components that can be freely shared among the participants, as well as components that contain proprietary information to which access is restricted. Experts from each participating country or organization, as part of a worldwide network, maintain access to their own databases and knowledge bases to which they have full access. In response to queries for information from other experts in the network, they can respond by releasing the results of the queries without compromise of any of the restricted information or data that underlie the response. Thus distributed data can be used to create information for the network with due consideration for data security.

Comparative analyses of interdicted material and archived samples (samples stored and available for analysis) can also be particularly helpful. These analyses allow the nuclear forensic expert to establish connections between the interdicted and the archived material or between the processes used to create them. As new signatures are discovered that depend on new analytical methods, it becomes increasingly important that databases be accompanied by archived material. Then, the old material can be re-analyzed by the new analytical methods and the resulting data analyzed for the presence or absence of the newly discovered signatures. Sample archives can include "real world" nuclear forensic samples, reactor fuel stock, other nuclear materials, and industrial radiation sources.

Statistical techniques

Any knowledge management system will rely on analytical tools and methods that are strongly mathematically based to elicit pattern, temporal trends, and group membership analyses. Multivariate analysis techniques e.g. multi-dimensional feature extraction, variable discrimination, and pattern classification, are used to investigate multidimensional data and form the "mathematical brain" enabling comparative and predictive signature analysis. Confidence articulation, based upon the results of these multivariate analyses, is an important requirement for these multivariate techniques.

Timelines

As production processes changes, the signatures inherent in the material will also change. Therefore, methods are needed to capture process knowledge and subject matter expertise as a function of time, e.g., material production process changes, to enable ready discrimination of signatures. The development of material production timelines is one method that should be effective in capturing the relevant process knowledge that would impact signatures throughout the nuclear fuel cycle. Comprehensive materials production timelines enable 1) narrowing of the applicable information field by using age dating information from a questioned sample and 2) capturing of the characteristics of relevant processes and process changes from cognizant experts that would impact signatures during material production.

Confidence in the conclusion

Analytical quality

Because the results of the nuclear forensics analysis and interpretation could be used as evidence in a criminal prosecution or affect international estimates of proliferation and threats of terrorism, it is essential that the data and their interpretation is credible. Adherence to chain-of-custody procedures will ensure that the analytical results correspond to evidence collected at the incident site. Proper quality assurance and quality control procedures within the nuclear forensics laboratory will ensure confidence in the analytical data. Nuclear forensic laboratories typically implement a recognized quality system, such as ISO 9000, ISO 17025, or ASCLD International [19-21]. A quality system encourages the establishment of documented procedures for sample control and analysis, which improves the repeatability of results and provides an enabling mechanism for continuous quality improvement. The establishment and registration of a quality system is important not only for its internal benefits, but also for the confidence that it inspires externally.

Precision & accuracy

As required by good analytical protocol, all analytical results should state the precision of the measurement and any potential sources of error not reflected in the precision. In the absence of bias, the precision of the measurement can place bounds on which sources and processes could produce material with the given signature. Although increasing the precision of a given measurement could narrow the field of potential sources or processes that produced the material as shown in Figure 3, it s often more efficient to perform additional measurements using independent techniques (techniques that verify the presence or absence of different signatures than the initial technique). The confidence in, and the specificity of, the interpretation often increase as more independent measurements are made as shown in Figure 4.

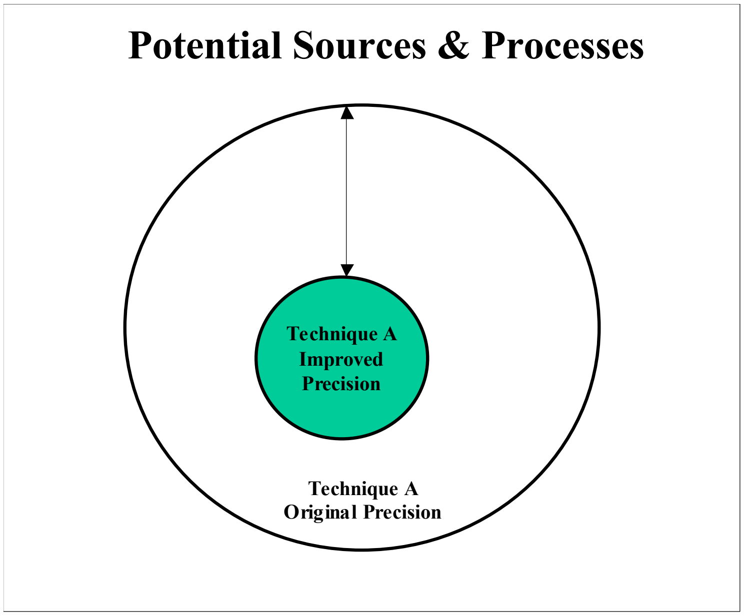

Figure 3. The Effect of Improved Precision on the Quality of Conclusions

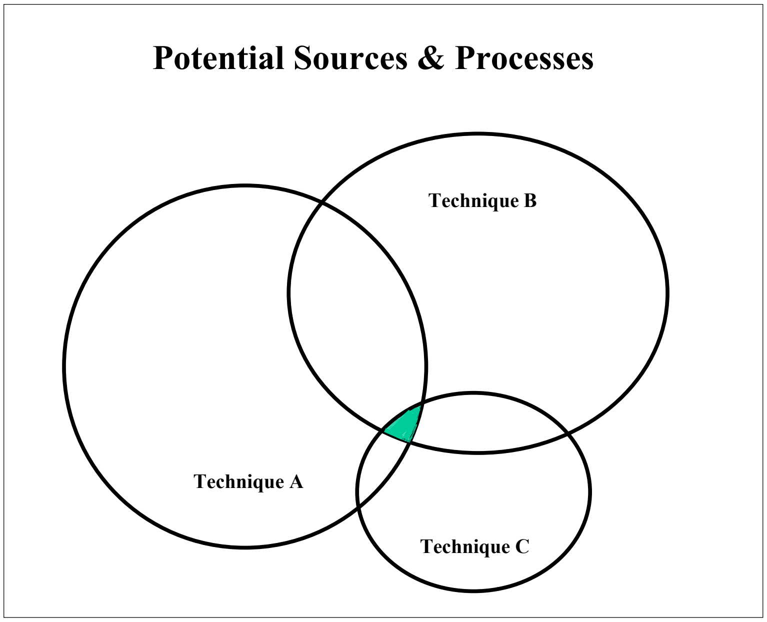

Figure 4. The Effect of Multiple Analyses on the Quality of Conclusions

Sensitivity

The sensitivity of the methods of analysis will be particularly important when the amount of evidence is small. In some cases, illicit traffickers may initially deliver only a tiny sample, which is purportedly representative of a much larger batch of material, to their customer. Even for interdictions of large amounts of material, the analytical techniques should be as sensitive as possible, because trace species are often significant components of a signature. However, as the sensitivity of the analysis increases, so does the susceptibility to contamination and other interferences. For example, the analyst might have to decide whether the Fe and Cr detected in the analysis is the signature of a certain manufacturing process or merely contamination from a stainless steel spatula used to collect the evidence.

Communication of results

All results and assessments must be communicated in the form of a technical report. Reports may be issued periodically during and after the conclusion of an interdiction event to keep decision makers apprised of recent data and insights from the investigation. For example, the laboratory could issue reports to coincide with the availability of results from the sequence of techniques and methods in Table 1 (24 hours, 1 week, 2 months). However, a final report must also be issued after the conclusion of the event. The nuclear forensics laboratory should identify all data and other information used in the assessment and include the rationale for the conclusion. The laboratory should also identify any information that conflicts with the assessment and why they are choosing to disregard or discount that information.

Ideally, there should be an unambiguous method of specifying the confidence in the conclusions to decision-makers. The international nuclear forensics community has not yet reached a consensus on such a method. It is difficult to summarize a vast body of evidence, each with its own uncertainty, with a single categorization. However, such a categorization must be made to communicate the strength of the evidence to decision makers who might not have the requisite technical background to rigorously evaluate all stages of data acquisition and analysis. Therefore, nuclear forensic researchers are seeking to develop and demonstrate methods to articulate confidence in nuclear forensics interpretations that are based on combining disparate data and information. The articulation of confidence when formulating conclusions based on disparate datasets is at the heart of enabling credible interpretations of nuclear forensics data.

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