Invited Paper

The Historical Evolution of Nuclear Forensics: A Technical Viewpoint

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Abstract. This paper presents the personal perspectives of the authors on the early development of nuclear forensics, beginning with the early 1990s. Independently, we started to work on nuclear forensics, recognizing that we were addressing a new set of questions. In 1995 an "International Conference on Nuclear Smuggling Forensics Analysis" was held at Lawrence Livermore National Laboratory, which ended by forming a International Technical Working Group (ITWG) as a forum for international technical cooperation on nuclear forensics. This conference also marked the start of our working relationship. Some of the early work of the ITWG is highlighted, notably the development of a "model action plan" and the execution of exercises in which scientists learned from one another. In the 2000s a number of countries and organizations started programs to make technical progress in developing nuclear forensics. Signatures are at the heart of the technical development, as they are crucially important for drawing technical interpretations from measurements. Some examples of cooperative research projects that include multiple countries will be described. Finally, based on our experience in the early evolution of nuclear forensics, we present some lessons learned regarding the development of a new field like nuclear forensics.

Thank you to the IAEA for inviting us to give this talk. Our talk will start with the early 1990s, when independently the two of us started to work on nuclear forensics, and describe how we started to collaborate in the mid 90s.

About two years after the Berlin Wall came down, a talk was given at Lawrence Livermore National Laboratory (LLNL) by a person who at that time served on an advisory board for the U.S. Department of Energy. He was on a mission to help guide the Lab, and in his talk he hit on a new problem. "How quickly and with what certainty (if any) could we identify the origin of a nuclear weapon unclaimed by anyone?" This potential use of what he called "an unattributed nuclear weapon" demanded, in his opinion, redirecting some of the traditional nuclear weapons research into addressing this problem.

Sitting in the audience was my Division leader at that time. He was galvanized by the challenge of an unattributed nuclear explosion, recognizing it as an important new question, and he immediately set out to do something about it. Drawing upon internal research funds, three scenarios were devised to help frame the problem and uncover issues.

I remember watching our nuclear weapons radiochemists work diligently on these scenarios. They would take the data and start to perform the types of data interpretation that were familiar to them. Before they knew it, they would be working hard on diagnosing the performance of the weapon.

Understanding the performance of the weapon was relevant to their investigation, but it was not the most important question they were asked to answer, the technical question, "What can you say about the origin of the materials and the design of the device?" In this early exploratory work, frequently the scientists would have to remind themselves that they were answering a question that was new to them.

I personally became directly involved in nuclear forensics in 1992 when I became the Nuclear Chemistry Division Leader. My interest in the attribution problem had already been piqued, and soon I started an effort to engage with other Labs to develop thinking about this new problem and how to approach it. By summer my Livermore team had completed an initial draft of a white paper, and we then sought to partner with other U.S. weapons labs. Eventually our efforts led to a meeting in the fall of 1993, for the stated purpose of "working-level discussions to define the attribution problem and the national capability, both current and future." The discussion emphasized the importance of recognizing that achieving attribution required information and experts from three spheres—intelligence, political and technical. At one point we developed a diagram that presented the many scenarios in which nuclear attribution would be useful, starting with the three basic scenarios of nuclear materials, a nuclear device, and a radiation dispersal device.

I then branched out to brief many people and organizations in the U.S. government on nuclear attribution. These briefings not only helped to promulgate our view on the need and nature of an attribution capability, they also helped to refine our thinking.

At the same time, we wanted to make some technical progress, so we re-directed some of our internally research funds to examine what could be determined about the origins of plutonium (Pu) from a detailed set of technical measurements. After all the writing and talking about what we might be able to do, it was good for the scientists to actually do some experimental work. This project led us to feature age dating, i.e. determining the time when the radio-chronometer was reset, as a key signature for nuclear forensics. The importance of age dating has become increasingly apparent ever since then.

Turning now to Europe in the early to mid 1990s, several significant interdictions of SNM (special nuclear material) brought to light the need for nuclear forensics. At the time of the seizures the Institute for Transuranium Elements was the only laboratory in Germany which could do the job. They were asked to assess the radiological hazard, the intended use and origin of the material, and to identify possible production sites. This required different procedures and measurements than were needed for their existing programs. The ITU radiochemistry lab was charged with tasks to verify operator declarations made under the EURATOM treaty by re-measuring samples taken at the plant. By this duty the institute acquired knowledge and capabilities of the civil fuel cycle in the EU. But for that work, the production date is already known, but for unknown material the history had to be established by making different types of measurements. One example is age-dating, but age dating was not the only new challenge: the production type was engraved in the material and had to be read from which followed directly the intended use of the material. To answer the question of where the material was produced, impurities and isotopic changes could give some hint but external records of production sites were essential to interpreting the data. Therefore ITU set up a database, partly from literature and partly from information provided under agreements with plant operators. These were new challenges for the Institute going beyond its acquired expertise.

One of the earlier interdictions was in Tengen near Konstanz. The Bavarian police searched the garage of a money counterfeiter and found by chance a container with a radioactive powder. The analysis at ITU showed a mixture of so called "red Mercury" and Plutonium (see table). The isotopic composition of the Pu was unusual. The Pu-239 was higher than could be produced by known nuclear reactors, consequently it must have been enriched. Moreover the Pu-metal was alloyed with gallium, which stabilizes the Pu delta phase over a greater temperature range.

In a second case a Colombian physician offered to sell Pu. The material arrived from Moscow in Munich, accompanied by the Columbian along with two Spaniards, where it was expected by the Bavarian police. Later the material was analyzed at ITU (see table). Their analyses confirmed the presence of Pu oxide, but it was mixed with U-oxide as well. The isotopic compositions are shown in the slide. They also found Li metal that was enriched in Li-6. ITU noted that the Pu was weapons-grade, and concluded that it was not from commercial reprocessing or from military production, and furthermore, it was produced by a non aqueous route. They concluded that it was residues from experiments to develop a MOX process.

Meanwhile, back in the U.S, my initial attempt at partnering with other U.S. weapons labs had floundered. So I decided to approach Pacific Northwest Laboratory, and within three months we produced a joint white paper "Attribution Assessment of Illicit Nuclear Materials." This white paper emphasized the importance of developing some type of attribution assessment team that would serve as the crucial link between the technical community doing the forensics measurements and those responsible for the overall investigation. The white paper's longest section described the sample flow and analysis sequence for a nuclear forensics investigation. A key emphasis was that measurement results needed to be interpreted using potentially a very broad set of expertise, with a goal to obtain a single integrated interpretation of all the technical results. The diagram that summarized this sample and information flow in a case investigation served as the basis for the later development in the international community of a "Model Action Plan."

During this flurry of paper studies and many briefings, one very important step was taken by one of the DOE offices we had been briefing. The office leader attended a P-8 meeting of nonproliferation experts in Ottawa in May, 1995. At that meeting he suggested holding an international meeting on the role of nuclear forensics in addressing nuclear smuggling. He offered that DOE would sponsor the conference and it would be hosted by LLNL. Of crucial importance was the participation of some key people who had been involved in analyzing nuclear materials that had been interdicted in Europe. So we were especially encouraged to hear that Lothar Koch from ITU would be attending, as he had led most of the known analyses of interdicted nuclear materials.

I served as the chair of the Conference, and I encouraged an agenda that would lend itself to open discussion and broad participation. The Conference included more than 70 participants from fourteen countries and organizations. Many people at the Conference noted that an especially distinctive feature of the Conference was the blend of scientists, law enforcement officials, intelligence experts, and policy personnel. Such a collection of people on a technical topic was almost unheard of

The culmination of the Conference got to the heart of the purpose for the Conference. After a panel discussion on the topic of "Mechanisms for International Cooperation and Next Steps," my key State Department representative gave me this direction—gather all the technical people and decide on what would be the best way to continue this type of international cooperation; meanwhile, the non-technical participants would take an extended break and then come back to hear our proposal.

The technical contingent recommended forming a Nuclear Smuggling International Technical Working Group (usually referred to simply as the ITWG). The conference endorsed this recommendation and we were directed to hold the first ITWG meeting in time to develop a Status Report that documented progress in technical cooperation on nuclear smuggling forensic analysis, and it should be done quickly so that it could be considered by the P-8 Nuclear Summit in Moscow in the spring of 1996.

The State Department lead at this conference cautioned me that the ITWG "should not be an every step ask for mother-may-I." Taking that approach too often in her experience led to no progress at all. Instead, she encouraged us scientists to be proactive, keep the ITWG technical and informal, and simply keep the political experts informed. By all means, she emphasized, do not let it become an official government activity. I followed that course of instruction throughout my 12 years of co-chairing the ITWG.

The first ITWG meeting was held at ITU early in 1996. An initial terms of reference was developed and a draft of the Status Report was discussed. Plans were made for the first international exercise, as the scientists were eager to begin working together on actual materials. We needed to do more than just talk, we needed to start a development effort that focused on the new question, i.e. how well can you identify source and history of a material based on nuclear forensics analysis? Of critical importance was the make-up of the group. The fact that the ITWG included most of the significant nuclear forensics capabilities in the world gave it technical credibility. Of equal importance was the strong presence of law enforcement and various security personnel, including notably the FBI and the Metropolitan Police of the United Kingdom (i.e. Scotland Yard).

It is important to note that national intelligence services have the dominant role in combatting smuggling of nuclear materials. But typically intelligence services do not have the capability to make nuclear forensic measurements, so they need to work with laboratories that do have that capability. In some cases, a country may have very limited or no capability to make nuclear forensic measurements, so if they wanted a nuclear forensic analysis, they would need to seek assistance from another country or go to an international organization. Therefore ITU offered its assistance in the framework of its role as part of an IAEA laboratory network.

After the ITWG finalized the Status Report it was forwarded to our respective governments. Subsequently, nuclear forensics was endorsed by the P-8 at the Moscow Nuclear Summit in April, 1996, as part of the illicit trafficking program. The ITWG set forth as its primary goal the development of a preferred approach to nuclear forensics that would be widely understood and accepted as credible. We laid out the primary technical elements, e.g. developing protocols, prioritizing techniques, facilitating assistance to countries.

In the early years of the ITWG, we focused on two main areas. The first was the development of a model action plan. It describes the steps that should be taken to respond to a suspected incident of illicit trafficking, and one early version is shown on the slide. This action plan stressed the importance of close interaction between scientists working on the nuclear material and traditional forensics by law enforcement. Ideally, all of the evidence developed by both communities should be brought together in order to reach technical conclusions. These technical conclusions would then provide a key input for further development of the case to answer the attribution question of who was responsible.

Any Model Action Plan has to take into account the wide differences among countries in the government structure and the level of capability for specific elements. For this reason IAEA and EC have tested the model action plan by conducting a number of exercises in various countries. For example, the TACIS program by the European Commission conducted exercises in a number of countries, according to the model action plan. Through this program, ITU also trained people and provided laboratory equipment and monitors in order to upgrade a country’s technical capabilities. Prior to the exercise, the model action plan would be adapted to their country’s specific circumstances. In some cases the results of the exercise led to changes in the national procedures for such an interdiction.

By that time of the fifth ITWG meeting, the ITWG had included participants from more than 30 countries and organizations. The second area of early focus by the ITWG was on exercises, and finally at the fifth meeting of the ITWG, the initial technical results of the first round robin exercise were presented. For the scientists, it was wonderful to finally have a meeting that had a much higher technical content, but for the non-scientists, it was too much. So we arranged to have a follow-up meeting that would include just the scientists who participated in the exercise. Basically, we experienced what we had hoped for—we learned from one another. We discussed observations that were difficult to interpret. We talked about the notion of developing a network of forensic experts who each had access to their own database on nuclear materials and might then share with others insights that could be gleaned from their own information. We also finalized a prioritization of techniques to be used in a case as a function of time. And it also stimulated development by some participants, for example, our U.S. team presented age dating that in addition to using the common Pu-Am chronometer, added several pairs of Pu and U isotopes. One Lab took note, and went home to develop that same capability and reported results the following year.

In year 2000, two significant steps were taken that represented a turning point for the development of nuclear forensics in the U.S. First, the HEU that was seized in Bulgaria in 1999 was sent to the U.S. for nuclear forensics analysis. We were given permission to use many of the techniques we had available. We not only measured the nuclear materials but also made many measurements on the associated non-nuclear materials. Since this work has been briefed quite a few times before, including more than a decade ago at the IAEA International conference on environmental monitoring and nuclear forensics, I will not comment on it further in this talk.

The second step was the establishment of a U.S. program on post-detonation nuclear forensics. A precursor to this step was a U.S. Dept of Defense task force study that addressed what it called unconventional nuclear warfare defense, unconventional because it specifically excluded nuclear weapons delivered by a missile. My boss at that time was on the task force, but he asked me to "carry the ball for him." Eventually that Task Force included in its recommendations the development of a post-det nuclear forensics capability in the Defense Department, and that recommendation was then acted upon.

By mid 2002 it appeared likely that a new U.S. government department for Homeland Security would in fact be established. A transition planning team had been formed, and I was asked to head up a large team of people at LLNL to assist the transition team by providing white papers for the counter nuclear terrorism R&D program. The white papers were well received, except for one—they weren't receptive to the one on nuclear forensics. That was a bummer! But I was able to arrange a briefing directly to the transition team leader in which I featured the work of the ITWG and also the U.S. work on the Bulgarian HEU seizure. It turned the tide, as he asked me to give my same brief to a key person on the White House staff, which lead to other developments within the U.S. government. And a few days later I was informed that nuclear forensics would be a part of the Homeland Security portfolio. This is what scientists sometimes need to be doing in order to achieve significant scientific and technical goals.

You may be wondering why I have made a point of the establishment of U.S. programs to actually develop the field of nuclear forensics. Although the ITWG was continuing to meet, and although we did some technical work, notably in the exercises, very little R&D was being done to develop nuclear forensics in any of the countries involved. Not only was it personally heartening to me to see the U.S. effort on nuclear forensics R&D take off, not long after a number of other countries involved in the ITWG also started their own programs to develop nuclear forensics capabilities.

The IAEA was a part of the ITWG from the beginning, but in the early 2000s we sought to develop a closer working relationship between the ITWG and IAEA. Most notably, the IAEA asked me to lead a team to write a draft on "Nuclear Forensics Support." In essence, it was the fullest description of the model action plan that the ITWG had worked on over many years. Eventually this document was published in 2006.

In 2003 the ITWG expanded its charter. Up to that time there was really no defined organizational structure for the ITWG. For the first 6 ITWG meetings, Lothar and I were co-chairs, and upon Lothar's retirement, I invited Klaus Mayer to take his place in co-chairing with me. So in the revised charter, we formed an executive committee and also identified Task Groups as the main vehicle for work to be done between annual meetings.

The non-proliferation experts groups of the G-8 had stimulated the start of the ITWG, and by 2005 I was considering further expansion of the countries participating in the ITWG. But I felt the need for some political backing in doing so, and eventually arranged to brief the NPEG in 2005. The brief by Klaus and I included an update on the ITWG work, but our main objective was to engage in a discussion on the future of the ITWG. I presented my personal view of a vision for international cooperation on nuclear forensics, and the role I hoped it would play. Then I posed the questions shown on the next slide. The thrust of the response—you are doing well, keep doing what you've been doing, and it's up to you whether or not to expand to include new countries.

I want to share what I consider to be at the heart of the technical development of nuclear forensics—signatures. Being able to make good and credible measurements is of course essential, but as I said many times to many people, what keeps me laying awake at night was the worry that even after we made good measurements, we still wouldn't know how to interpret the results.

Here is my own personal vision for signatures-- a validated set of signatures that uniquely distinguishes the origin and history of nuclear and radiological materials, and that this needed to be done for materials across the globe and the signatures needed to cover the entire life cycle of nuclear materials. Developing better signatures is the cornerstone for improving specificity, accuracy, and credibility of technical judgments. The long-term goal of signatures research should not only be to determine what attributes help most to constrain the origin and history of a material, but it should also determine the mechanisms that control signature development.

A heartening trend that has accelerated in recent years is cooperative research projects that includes multiple countries. Two years ago I created these slides that list some of the projects that the U.S. was involved in with other countries; it's quite a list. Here's a technical summary of two of them. Five laboratories conducted research to validate age dating of HEU using the U-234/Th-230 chronometer. The graph shows excellent agreement in one test case. A second example is a project that has involved a number of countries and organizations; goal is to be able to identify uniquely the origin of uranium ore concentrates. It uses isotopic, chemical and physical properties, and an analysis tool has been developed that identifies the source of UOC samples with about 90% accuracy.

This is just a very brief summary of the first 15 years of the development of nuclear forensics. Over the past couple of years I was afforded the opportunity to write a more detailed history of nuclear forensics, from my personal point of view. My goal was to develop the lessons that I've learned regarding the development of a new field like nuclear forensics. So I will close by sharing these lessons:

- When you are trying to develop something new, other people will naturally try to fit it into their old "narratives" i.e. their existing programs, perspectives, and concerns, and it will take a long time to overcome this tendency

- Conflicting perspectives between interested organizations have impeded (and probably will continue to) the understanding and development of nuclear forensics
    - The development of nuclear forensics requires intersection of multiple narratives, i.e. scientists, law enforcements, intelligence, and policy makers from different parts of the government, thereby compounding the difficulties in achieving a coherent development

- Serendipity played an important role in the development of nuclear forensics

- International cooperation is necessary and difficult
    - It has been important to keep technical cooperation as informal as possible in order to make progress

- Developing new signatures is central and challenging
    - Challenging scientifically—takes a particular type of conceptual thinking and it is difficult a priori to identify what progress will be made in developing new signatures
    - Challenging to get non-scientists to pay attention to signatures, for the drive to an operational capability can leave signatures R&D behind

- It's OK to be persistent—if you're right about it being important—I continue to persist in my belief that nuclear forensics is very important!

Invited Paper

Development of Nuclear Forensics in Russia

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As was noted in the communiqué of The Hague Nuclear Security Summit-2014 – "Nuclear forensics is developing into an effective tool for determining the origin of nuclear and other radioactive materials and providing evidence for the prosecution of acts of illicit trafficking and other malicious acts".

In the Russian Federation where the issues of the nuclear security strengthening and reduction of risks of the nuclear terrorism are assigned high priority, much attention is also paid to the nuclear forensics development, taking into account the existing international experience as well.

Therefore, the IAEA initiative to conduct this international conference on advances in nuclear forensics seems quite timely and useful. We hope that the specialists participating in the conference will learn a lot and will exchange their opinions on this important part of the nuclear security. We also hope that the issue of terminology will not be forgotten during these discussions. The current interpretation of the term "nuclear forensics" varies from using nuclear methods in traditional forensics to methodologies of determining a place of origin of nuclear material.

At the same time, considering the nuclear forensics history it should be mentioned that this notion has been put by the international community into wide use relatively recently - with the appearance of Global Initiative to Combat Nuclear Terrorism and a number of nuclear security summits. However, criminalist actions concerning the crimes linked with nuclear and radioactive materials were performed much earlier. In this connection, there is ground to believe that the world nuclear forensics history may be considered taking its development in Russia as an example.

Let me begin with the fact that the nuclear forensics in Russia is developed in close cooperation between the law-enforcement authorities performing criminal investigations and experts in nuclear and radioactive materials. The development has not begun from scratch. Looking back, we should say that certain methods of what is now called nuclear forensics were used in the Russian investigative and court of justice practice from the middle of the previous century when the intensive nuclear program development and radioactive material application for industrial and medical purposes started.

But in early 1990-ies, these separate methods started to form a certain system due to a necessity to investigate the cases of nuclear and radioactive materials illicit trafficking. Already at that time it was possible not only to determine origin of the intercepted material, but also to narrow the circle of suspects significantly.

V.P. Kuchinov

Today, in Russia the following three main tasks are being solved in the area of the nuclear forensics:

1) Providing the law enforcement investigation with the data on the nuclear and radioactive materials that are intercepted from the area beyond the regulatory control as well as providing the information of the transfer routes of these materials, and on people connected to the nuclear and radioactive material illicit trafficking;

2) Disclosure of false charges and counteraction to provocative acts;

3) Deterrence of criminal intent due to the possibility of their guaranteed disclosure which provides the unavoidability of punishment for illegal actions.

From the criminal prosecution and a number of criminalistics approaches point of views, the illicit trafficking in nuclear and radioactive materials (ITNRM) does not differ from existing and much more widely spread illicit trafficking in precious metals, weapons, drugs, explosives and other prohibited for free circulation chemicals, etc. Therefore, the investigative basis as described in the Russian Federation Criminal Code, the Criminal Procedure Code and the Judicial-Expert Activities in the Russian Federation turned out to be quite suitable for ITNRM incidents investigation as well, and no legal framework development for such investigations in Russia is needed.

On the other hand, the Russian developed nuclear complex, the experience of developing and manufacture of a wide range of materials for both peaceful and military purposes provided a significant number of experts in nuclear and radioactive materials and the existence of advanced analytical laboratories for these materials' parameters and properties study.

Thus, the law enforcement officials' task in the Russian nuclear forensic community is mainly incorporating in the developed approaches and procedures the provision of criminal law. The nuclear and radioactive material experts in their tern have to develop new methodologies, and adapt the existing ones, for the reliable identification of materials with unknown origin and for the analysis characteristic of samples of the physical evidence found at the scene of the crime or in connection with the crime.

Further development of understanding the importance of counteraction to the nuclear terrorism threat and illicit trafficking of nuclear and radioactive materials was implemented in the Russian Federation Law of December 1, 2007 No/ 317-FZ Art.15. According to this law, the Rosatom State Corporation was entrusted with "the organization, within its competence, of the activities to combat the threat of nuclear terrorism and illicit trafficking in nuclear and radioactive materials"; besides, with "the organization and conduction of criminalistics and other expertizes for the identification of nuclear and radioactive materials and radioactive waste withdrawn from illicit trafficking".

On the basis of this law, in 2009 an Information and Analytical Centre (IAC) for the identification of nuclear materials was set up in Rosatom State Corporation, and was imposed with the task of performing the analyses and identification of the nuclear materials with the unknown origin. The key role in the Centre activities is played by JSC "Bochvar VNIINM". However, the laboratories of V.G.Khlopin Radium Institute, NP "Microparticle analysis laboratory", Federal Medical and Biological Centre laboratories are also engaged in this work. These four institutions constitute a network of Russian analytical nuclear forensic laboratories. Additionally, the laboratories of other institutes of both the Rosatom Corporation and other organizations can also be invited for the particular work.

The network laboratories solve the following analytical tasks:

- Determining the material element composition and isotope composition of uranium and plutonium in the materials and separate microparticles.
- Measuring the content of isotopes-chronographs.
- Measuring the content of impurity elements.
- Determining the morphological parameters of nuclear and radioactive material fragments and microparticles.
- Measuring the content of radionuclides in the samples.

It should be mentioned that all these tasks had been solved by the Russian analytical laboratories prior the creation of the network of the nuclear forensic laboratories, within the framework of other tasks performed in connection with nuclear monitoring and geological exploration.

In the same 2009, with the IAEA assistance, the Information and Analytical Centre (ITNRM IAC) was set up in the Rosatom State Corporation for collecting and processing the information on the cases of illicit trafficking in nuclear and radioactive materials. This IAC performs the interaction with the IAEA database on the INTRM cases at the Russian Federation territory which became known from the law enforcement authority and mass media information.

In addition to law enforcement authorities and nuclear material experts, organizations of other Russian Federation authorities are involved in the work to combat INTRM: Russian Ministry for Defense, Emercom of Russia, Federal Custom Service of Russia, and Rostehknadzor.

A significant difference of handling the physical evidence compared with analysis made during fulfilment of other tasks is connected with the need to provide the guarantee that from the moment of the withdrawal to the presenting in court, the physical evidence was not substituted and did not change its properties. Following the procedure determined by the Criminal Code, Criminal Procedural Code and the Law on Judicial-Expert Activities in the Russian Federation ensures such guarantee.

In accordance with this procedure, any object shall become a physical evidence only if it is withdrawn by an investigator and documented in due order. Each object or material considered physical evidence shall be packed into a container. Any movements of the physical evidence shall be documented.

Nuclear and radioactive materials shall be put to a special container in compliance with the radioactive material handling rules. The same rules shall be observed when performing any operations with the radioactive physical evidence. Therefore, the three laws mentioned above, together with Radiation Safety Norms determining the rules of radioactive material handling, form a legislative basis in the field of nuclear forensics in Russia.

For identification of the intercepted nuclear materials, a comparative analysis of the intercepted material and one or several materials from among those manufactured in the country and having characteristics close to those of the material concerned, is performed. For determining the list of materials under suspect, the information from relevant Russian enterprises databases is used. But only the coincidence of the analysis results of the intercepted material and one or more samples from the material archive shall be a ground for conclusions on the detained material origin.

However, if the comparative analysis cannot be performed because of the absence of a corresponding sample in the archive, any information available for the expert analysis shall be used, with the understanding of the fact that all kinds of comparison, excluding the coincidence of comparative analysis results, require additional expert study of actual and possible variations of results or data.

Based on this practice and taking into consideration the experience of nuclear material databases use during the actual study, with the clear understanding of the rare and limited character of such use, and also observing the existing procedure of nuclear information security, a conclusion was made in Russia on the inexpediency of developing so-called National Nuclear Forensic Database. The availability of the information on nuclear materials stored in special databases is also taken into account, as well as sufficient timeliness in providing this information to the investigators.

It should be pointed out that the practice of performing investigations linked with illicit nuclear and radioactive material trafficking showed also the necessity of analyzing not only samples of bulk NRM but also their microparticles. In the absence of the intercepted material and also when the material is determined but may be manufactured at different enterprises the analyses results of individual microparticles of the objects taken as physical evidence can become the key to a successful investigation.

The analysis of individual microparticles when investigating actual incidents proved its informative value, for example, during a case where the route of persons having contacts with NRM and the actual manufacturer of the material intercepted in a container were determined. Judging by the material characteristics it could be concluded that this material has been manufactured at any of the two enterprises, and only the analysis of industrial dust microparticles at the container surface allowed to unambiguously identify one of them as the enterprise where the stolen material was produced.

Only the analysis of individual microparticles can solve the task of identifying the material if a powder consisting of various materials microparticles is detained. Besides, the microparticle analysis can be the only informative approach in the situation when fragments of various materials are dispersed during an incident and can be present in various samples from the place of incident.

In general, in can be stated that nowadays the network of Russian nuclear forensic laboratories is available and can solve any nuclear forensic tasks. It can analyze both bulk samples of nuclear and radioactive materials and their small fragments and individual microparticles. Nevertheless, the network is constantly developing taking into consideration procedural and methodological recommendations worked out under the auspices of the IAEA.

A special significance in the procedure of criminal trials connected with nuclear and radioactive materials beyond the regulatory control plays the presentation of the expert materials to court. All the relevant materials are presented in the Russian court only as expert opinions or evidence in the form of printed documents. Preference is given to the expert opinions based on the comparison of simultaneous analyses results. These documents shall also be mandatorily included as part of the criminal case file to be considered by the court, the prosecutor and the lawyer. If necessary after presenting the expert opinion to the court the expert gives additional oral statement during the examination in court for clarifying some statements of the opinion and precluding misunderstanding.

An extensive international cooperation in the nuclear forensics field should also be mentioned as it helps to speed up the Russian potential development in this area.

We believe that the activities of the International Technical Working Group (ITWG) on the nuclear forensics in which Russian experts work among others, as well as continuation of a wide international cooperation on nuclear forensics in frame of the IAEA, GICNT and Interpol are very important.

Discussing the nuclear forensics at this conference today, I would like to stress that we see the further development of the nuclear forensics in Russia both as the analytical methodologies advancements and further strengthening interaction between analysts and law enforcement officers and certain updating of regulatory documents. For example, the revision of “Generic plan of response to ITNRM incidents” has been started in compliance with the IAEA recommendations “Nuclear Forensics support”, series 2. We also believe that achievements which we will learn during this conference also will assist us in this work.

Invited Paper

Historical Evolution – Nuclear Forensics: A Political Viewpoint

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Ladies and Gentleman,

I feel honoured to be invited by this conference. It was 5 years ago that I heard the term nuclear forensics for the first time when I learned that my country had proposed to put this topic on the agenda of the Nuclear Security Summit in Washington. In the past two years nuclear forensics was an important part of the preparations of the 2014 Summit in The Hague.

What I will do is to provide you with a view on the nuclear forensic discipline "from a distance", putting it in historical perspective and highlighting its importance for society.

Nuclear Forensics is literally the fusion of two sciences – and two different worlds. It is a relatively young discipline. The handshake took place in the nineties of the last century, after the seizure of batches of highly enriched uranium and plutonium that escaped regulatory control in the aftermath of the Cold War. Samples were analysed to gain insight into where these seized materials may have originated.

It is one thing to trace back the origin of materials, it is quite another thing to use that knowledge to prosecute smugglers. National laws against illicit trafficking were weak or nonexistent, and there was not a strong emphasis on law enforcement.

Several incidents triggered a change. One of these was the Bulgarian seizure of 4 grams of 73% enriched uranium in 1999. The Bulgarian authorities could not prosecute the traffickers – and they were absolutely not the only country – since there were simply no laws that forbade it. As a result, many countries including Bulgaria and the Netherlands strengthened their nuclear and criminal laws appreciably.

1. Developing an international norm

Also on the international level there was recognition that something had to be done. The Nuclear Forensics International Technical Working Group (ITWG) recognized, a few years after its foundation in 1995, that nuclear forensics methods should be applied in such a way as to ensure that evidence withstands scrutiny in court. ITWG formed a 'First Responders / Evidence Collection Task Group' with a focus on techniques for the preservation of evidence.

Then came 9/11. The world more than ever realised that nuclear and radioactive materials might be used by terrorists. And how crucially important it was to provide police and judiciary bodies with tools to apprehend perpetrators. Amongst others, the IAEA convened an International Conference on Advances in Destructive and Non Destructive Analysis for Environmental Monitoring and Nuclear Forensics in Karlsruhe in 2002, which was widely attended by international experts.

Still in the early years of the century the advance of nuclear forensics was a matter of common sense: many countries felt that everything should be done to bring nuclear smugglers and persons with even grimmer intentions to justice. They amended their laws to make smuggling – and certainly also the unlawful use – of nuclear and radioactive materials a crime. That was reinforced with the adoption, under Chapter VII of the UN Charter, of SC resolution 1540 (2004). From then on States had to develop and maintain effective border controls and law enforcement efforts, with the aim to detect, deter, prevent and combat illicit trafficking and brokering of items that can be used for weapons of mass destruction.

But even more significant was the signing and entry-into-force of the 2005 International Convention for the Suppression of Acts of Nuclear Terrorism (ICSANT). Art. 5 of that Convention stipulates that States shall establish as criminal offences under their national laws the illegal possession, threat of use and the use of nuclear and other radioactive material, and to make those offences punishable by appropriate penalties.

From a national legal requirement it was in the nineties it became a clear and specific international norm. States had to act on it. And equally important: the police and the public prosecutor had to apply appropriate measures. Nuclear forensics was thus embedded in the international legal system.

2. New initiatives

From thereon nuclear forensic initiatives developed in rapid pace.

In 2009 preparations started for the Nuclear Security Summit, convened by president Obama. As I mentioned earlier, the Netherlands strongly advocated making nuclear forensics part and parcel of the fight against and the prevention of nuclear terrorism and illicit trafficking. It was indeed included in the work plan and communiqués of the 2010 Washington and subsequent Summits.

In 2011, a so called “gift basket” was created by the Netherlands as a platform for action for nuclear forensics within the summit process. At the same time, a nuclear security working group was set up under the Global Initiative to Combat Nuclear Terrorism (GICNT), chaired by Australia.

In preparation for the 2014 Nuclear Security Summit in The Hague the Netherlands Forensic Institute developed together with experts from 30 countries the “Innovation Pathway for Forensics in Nuclear Security, 2014-2019”. The results were presented at the Nuclear Knowledge Summit on 20 March 2014 in Amsterdam. The recommendations included in this Innovation Pathway focused on further development of the national response plans, an international knowledge platform for experts, a mechanism to share knowledge and exchange information, the development of investigating equipment and an international train and exercise programme.

3. Past, present and future

I have mentioned quite a number of initiatives. It might seem that there is an overlap of activities, but in fact each of them has its own aims and methods. To give you an example: the NSS has created a website with an expert platform, a glossary of terms with the aim of harmonising terms and definitions, and it has worked on a compendium of methods. GICNT has focused on training, exercises and workshops. In practice these are complementary activities in which often the same experts are participating.

These are some of the highlights of past activities. This international conference here in Vienna comes at an important moment: it takes stock of national and international developments, putting it all together, posing questions, advocating new methods and looking into the future. Equally important: it provides a unique opportunity for networking. All in all a very valuable initiative by the IAEA, that I highly welcome.

Let me highlight one of the **interesting future activities**. In the framework of GICNT three countries, Canada, the USA and the Netherlands will be organizing a “mock trial” at the Peace Palace in The Hague, the Netherlands early March next year. This mock trial will focus on the admissibility of nuclear forensic evidence and the role of the nuclear forensic expert in a criminal court applicable to both common and civil law systems. In simple words: there will be a scenario of a nuclear criminal event, a police investigation, an indictment related to nuclear or radioactive materials, defendants, evidence and finally: a court case. The most important question here is: can the nuclear forensic evidence be successfully used in court? Will it convict the perpetrators?

The underlying rationale for this mock trial is of course that the entire judiciary system gets few opportunities to practice nuclear cases. To ensure that the proceedings will be realistic and genuine, a number of regular legal officials, judges and barristers will participate in the trial.

Elaborating on the future: what will be the new frontiers in nuclear forensics? In my view **Cyber security techniques** will be in the top three. Cyber is getting an increasingly important place in the nuclear security domain. And it goes without saying that nuclear forensics should follow suit, developing cyber forensic investigation methods as a matter of high priority. I have no doubt that this issue will be raised and discussed in the coming days.

4. Summing up and Conclusion

Let me sum-up and conclude by the following points.

Nuclear forensics is a relatively young discipline, but one undergoing a rapid development and transformation. Successful nuclear forensics methods:

1. have an intrinsic preventive effect: they deter criminals and trace terrorists;

2. should be closely linked with the rule of law;

3. must be applied by States to comply with the international legal norms (ICSANT and the mandatory Security Council Resolution 1540); these instruments oblige States to prosecute criminals and terrorists who are possessing or using nuclear and other radioactive materials;

4. will stimulate international cooperation, since no country can provide all the best practices, and since the prevention of nuclear terrorism and illicit trafficking is almost always trans boundary business.

I wish this conference every success in its efforts to create a more secure world.

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20 Years of Nuclear Forensics at ITU: Between R&D and Case Work

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Abstract. Nuclear Material is kept under a stringent system of national control and international verification. This includes physical protection and safeguards measures. Still, in early 1992 the first case of "nuclear smuggling" was detected with the seizure of a number of uranium fuel pellets. Those pellets were taken to the Institute for Transuranium Elements (ITU) for closer examination. Since then, more such incidents have been reported and the phenomenon has been understood in a broader sense and referred to as "illicit trafficking". The methodology applied for the examination of the nuclear material (and any associated material) and the respective interpretation of data is referred to as "nuclear forensic science". From the onset of "Illicit trafficking" in the early 1990's till today, the phenomenon has changed and also the analytical and interpretational methods have evolved.

In more than two decades of involvement in nuclear forensic investigations at ITU, the analytical techniques were developed further, adapted to the specific needs and perfected with regard to timeliness and reliability of results. Collaboration with authorities involved in the response process was strengthened and their specific needs have been included in the nuclear forensics methodologies. A systematic approach was developed for investigating samples of seized material, and a comprehensive, though efficient, process for conducting the various analyses was implemented. Taking into account that nuclear forensic samples are always unique in terms of the circumstances of the incidents, of the nature of the material and of the objectives of the investigation, the scientific investigations on the actual nuclear material are carried out under the same boundary conditions. On the other hand, we have to include in our considerations also the fact that illicit nuclear trafficking is a border crossing problem. In consequence, also the nuclear forensic investigations need to take this aspect into account. As can be seen, nuclear forensics is not only a multi-disciplinary branch of science; it involves further dimensions such as law enforcement, international safeguards, radiation protection etc. The paper will present selected examples of casework conducted during the past 20 years and illuminate recent methodological developments.

1. Introduction

The phenomenon of illicit trafficking of nuclear and other radioactive material appeared in the early 1990's. Since then, illicit trafficking, the associated risk of nuclear proliferation and the threat of nuclear terrorism remain areas of international concern. Continuous efforts for further enhancing nuclear security have been undertaken. This includes the prevention and detection of and the response to illicit incidents involving nuclear or other radioactive material. Nuclear forensic science is a key element of nuclear security. It is a relatively new discipline, which emerged with the first incidents of "nuclear smuggling" that were detected in 1992 in Europe. Nuclear forensic science, colloquially referred to as "nuclear forensics", aims at providing clues on the history of nuclear materials of unknown origin [1, 2]. This includes hints on the place and date of production and on the intended use of the material.

Such information is of relevance to nuclear security (e.g. in order to improve physical protection and safeguards measures at the pace of theft or diversion for preventing future diversions), or to prosecution (e.g. for providing evidence related to criminal acts involving nuclear or other radioactive materials). This information is obtained by measuring various parameters, such as major constituents, isotopic composition of the major elements or trace elements, products of radioactive decay, chemical, elemental, anionic or organic impurities, macroscopic appearance, microstructure, molecular composition and age [1-6]. Nuclear forensic science from its very beginning drew upon a variety of different analytical techniques already available from nuclear safeguards, isotope geology or other areas [1].

2. Case Work

The first illicit trafficking incidents were reported in 1991 in Switzerland and in Italy. In the subsequent years numerous incidents were reported from central and eastern European Countries. Most of the seized nuclear material was taken to ITU for detailed material analysis. A new discipline in science was born: nuclear forensics. At the time, however, no systematic approach and no established methodology for analysing nuclear material of unknown origin were available. The analytical schemes were incident driven and established on an ad-hoc basis: nuclear forensics was still at its infancy.

2.1. The First Decade

The first case, where the intercepted material was subject to a detailed investigation occurred in 1992 in Germany and involved some 72 LEU pellets with a total mass of more than 1 kg. The national authorities asked ITU to analyse the material for obtaining hints on the potential origin of the material. During the following three years, twenty-one investigations of materials seized in Germany were performed. The circumstances of all of these incidents pointed at intentional smuggling of nuclear material supposedly preceded by a theft of nuclear material in the country of origin of the material. The majority of the cases concerned uranium fuels that were intended for use in early-generation graphite-moderated or pressurized-water nuclear power reactors. The most serious incidents involved kilograms of highly enriched uranium, several hundred grams of plutonium mixed oxide, and weapon-grade plutonium. Table 1 provides an overview of the illicit trafficking incidents where the nuclear material was investigated at ITU.

Table 1 Overview of seized material analysed at ITU in the period 1993 to 2003

Find No.	Date	Place	Seizure
1	05.03.1992	Augsburg	72 LEU pellets, 1099 g
2	07.07.1992	Berlin	Metal rod, U_{nat}, 1772 g
3	09.10.1992	Windsbach	22 U_{nat} pellets, 320 g
4	13.10.1992	Taufkirchen	54 LEU pellets, 843 g + U_{nat} powder, 2017 g
5	11.11.1992	München	1 Pu ionisation source
6	03.12.1992	München	383 Pu ionisation source
7	21.12.1992	Böblingen	Metal cylinder, U_{nat}, 2528 g
8	24.12.1992	Nürnberg	1 Pu ionisation source
9	17.02.1993	München	2 LEU pellets + 2 U_{nat} pellets, 51 g
10	16.03.1993	Waidhaus	1 LEU pellet, 14.9 g
11	00.04.1993	Berlin	U_{nat} powder, 3.9 g
12	15.07.1993	Mainz	3 pellets, U_{nat}, 48 g

13	10.05.1994	Tengen	Pu in “red mercury” powder, 56 g
14	06.06.1994	München	2 LEU pellets, 20 g
15	08.06.1994	Bavaria	DU in lead container, ~ 1 g
16	15.06.1994	Landshut	HEU granulate, 0.8 g
17	08.07.1994	München	189 LEU pellets, 894 g
18	08.08.1994	Pforzheim	2 LEU pellets, 19 g
19	11.08.1994	München	U and Pu powder, 560 g + Li metal, 201 g
20	06.09.1994	Berlin	Cs_{nat} metal
21	14.10.1994	Karlsruhe	1 U_{nat} pellet, 15 g
22	29.05.1996	Ulm	206 LEU pellets, + U_{nat} powder, 1.8 kg
23	27.02.1997	Karlsruhe	Parts of spent fuel assembly
24	00.07.2001	Karlsruhe	Contaminated items

A total of 24 incidents were analysed at ITU during the first decade of "nuclear smuggling". As can be seen from table 1, almost half of the cases involved uranium fuel pellets. The need for attributing pelletized nuclear material to a reactor type and to a potential fabrication site triggered a joint project between ITU and the A.A. Bochvar All Russia Research Institute of Inorganic Materials (VNIINM) for jointly establishing a nuclear materials database that compiles data of Russian and Western European fuel manufacturers [7]. This database served first of all as analytical guidance in order to optimize the analytical process and to focus on the measurement of those parameters that would be the most useful for identifying possible origin and intended use of the material.

In parallel to the case work, research and development activities were started in order to establish the scientific basis for nuclear forensic investigations.

2.2. The Second Decade

After the "hype" of illicit trafficking in the first half of the 1990's, the number of cases reported in central Europe decreased. With the transition to first decade of the 21st century another type of incidents started being reported in increasing numbers: radioactively contaminated scrap metal. Table 2 provides an overview of those cases of contaminated scrap metal which involved nuclear material.

Table 2 Overview of incidents in the period 2003 to 2013 involving scrap metal contaminated with uranium

Find No.	**Date**	**Place**	**Seizure**
26	16.12.2003	Rotterdam, NL	Unat (yellow cake)
27	30.03.2006	Hennigsdorf, D	HEU (contaminated scrap)
29	02.06.2006	Baarn and Bunschoten, NL	Various DU and Unat. powder
32	00.11.2008	Dordrecht, NL	Contaminated metal scrap
33	00.07.-11.2009	Dordrecht and Rotterdam, NL	Contaminated metal scrap
34	02.2010	Tornio, FIN	Contaminated metal scrap

35	04.2010	Rotterdam, NL	Contaminated metal scrap
36	04.2010	Dordrecht, NL	Contaminated metal scrap
37	06.2010	Dordrecht, NL	Contaminated metal scrap
38	09.2010	Dordrecht, NL	Contaminated metal scrap
39	10.2010	Dordrecht, NL	Contaminated metal scrap
41	21.03.2011	Dordrecht, NL	Contaminated metal scrap
42	17.05.2011	Dordrecht, NL	Contaminated metal scrap
43	02.11.2011	Rotterdam, NL	Contaminated metal scrap
44	03.2012	Moerdijk, NL	Contaminated metal scrap

The samples from these incidents typically showed higher levels of chemical impurities and did not offer macroscopic features (as additional signature) supporting a nuclear forensic interpretation. Consequently, the isotopic composition of the major element (uranium) provides the essential nuclear forensic information. Often, the samples consist of mixtures of materials, as can be revealed by micro-analytical techniques, such as secondary ion mass spectrometry (SIMS). This is illustrated in fig.1 showing several items carrying uranium contaminations (Find 38 in table 2), detected at a scrap metal recycling facility. Samples were taken from all the individual items and taken for analysis to ITU. Chemical analysis provided an average of the isotopic composition of the uranium deposits. It proved to be more useful in this case, however, to grind the material to a fine powder and to analyse individual particles by SIMS.

Figure 1 Items carrying radioactive contamination that triggered a radiation alarm at a scrap metal recycling facility. The items were singled out and subject to initial measurement by the competent national authority. Samples were taken to ITU for further analysis.

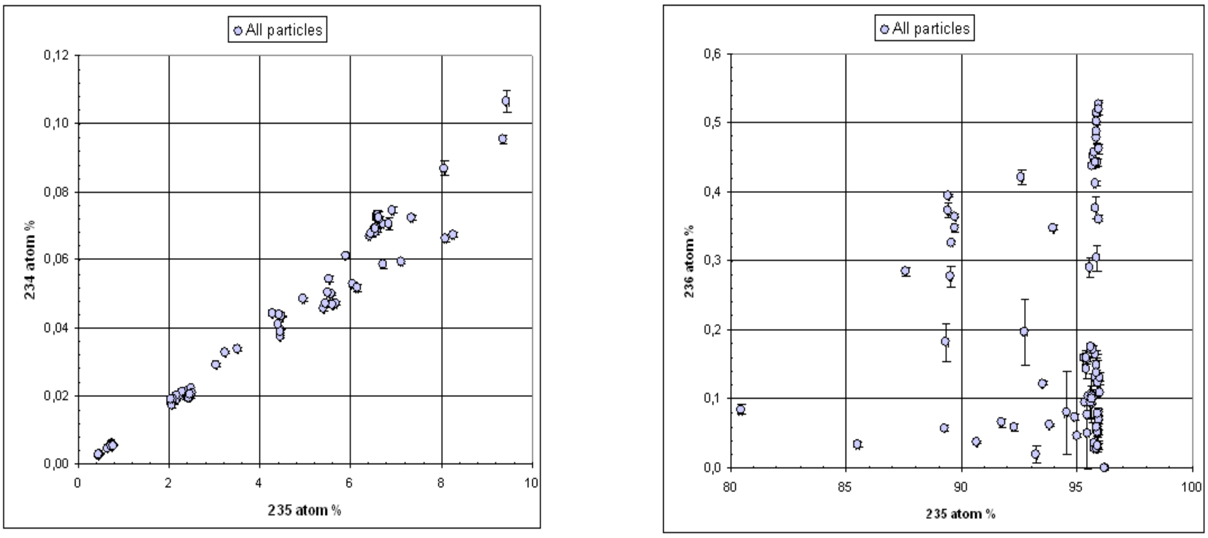

Figure 2 Measurement results obtained on individual particles by SIMS indicating distinct populations of low enriched uranium (left graph) and highly enriched uranium with ^{235}U abundances up to 96% (right graph).

The SIMS measurement revealed the contamination to consist of a mixture of different enrichments, as shown in fig. 2. The ^{235}U enrichment was found to range up to 96 mass% . Such highly enriched uranium is very rarely encountered. One application, however, is in lightweight nuclear reactors used in space (e.g. TOPAZ), thus providing also hints on the facility where the uranium was processed and where the contaminated metal possibly originates from.

3. Research and Development

Basically, nuclear forensics relies on the fact that certain measurable parameters (e.g. chemical impurities, isotopic composition, macroscopic appearance, microstructure) in a sample may be combined to form a characteristic "signature" for the given material. This signature provides hints on the history of the material, including the source material it was prepared from, the processes used for its transformation, the intended use, the date of production and possibly the origin of the material. The main challenges consist first of all the identification of those parameters providing useful hints on the history of the material and secondly, the interpretation of the analytical data. Thus, R&D activities focus on signature development and on method development.

The pattern of rare earth elements (REE), for example, has proven to be a useful signature for provenancing natural uranium. A method was developed for group separation of the REE (i.e. separating the REE from uranium without changing their relative abundance [8,9]. Also the isotopic composition of certain chemical impurities (e.g. Sr, Nd, or Pb) may provide hints on the geological environment the uranium was mined from. The products of the radioactive decay of uranium (e.g. ^{234}U/^{230}Th) are another important signature providing information on the last chemical separation of the nuclear material, usually referred to as the "age" of the material [10]. Classical methods of molecular spectroscopy such as Raman or Infrared-spectroscopy are also applied for identifying the chemical compound and anionic impurities [11]. The latter may point at the chemical processing the material was subjected to. Some of these aspects will be presented in some more detail in dedicated papers at this conference [12-15].

4. Conclusion

Nuclear forensics is a key element of nuclear security. Starting with the first cases of "nuclear smuggling" that were reported in Europe, ITU got closely involved in nuclear forensic investigations. In this period samples of nuclear material from more than 40 nuclear security incidents were investigated and information on the history of the material, its intended use and its potential origin was provided to the competent national authorities. The application of nuclear forensics methodology was backed by a comprehensive research and development program which results validated methods and useful nuclear signatures, ultimately supporting credible nuclear forensics conclusions.

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