Nuclear Forensics. The Science beyond Fission

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Abstract

This article aims to offer a study on the origin, development and current state of nuclear forensics. This still new discipline dedicates its efforts to the examination of nuclear and radioactive materials found out of control, employing for this purpose various analysis procedures, all in the course of a police investigation, and its final purpose being able to attribute an origin to these materials. The use of these materials by terrorist organizations is considered by the main actors within the international community as a serious threat to peace and security. In this context, having the appropriate knowledge about the origin of these sensitive materials is a necessary condition so that the most consistent security measures can be adopted that can help prevent their disappearance. All this with the firm purpose of preventing them from being finally employed in the course of a terrorist attack.

Keywords: Terrorism, nuclear, radioactive, forensics, investigation, security.

1. Introduction

On April 13, 2005, the United Nations General Assembly adopted the International Convention for the Suppression of Acts of Nuclear Terrorism, the preamble of which stated that "acts of nuclear terrorism may result in the gravest consequences and may pose a threat to international peace and security". This is an opinion considered and shared by most of the relevant actors on the international scene, who consider the threat coming from nuclear terrorism, despite the scarce known antecedents when compared to terrorism carried out with the traditional media, as real and significantly detrimental to the maintenance of the established order.

The importance of this threat derives, of course, from the infinite destruction that a nuclear weapon is capable of producing, as witnessed by the tragic experiences that occurred in the Japanese cities of Hiroshima and Nagasaki in the epilogue of World War II and the hundreds of nuclear tests carried out on a wide variety of scenarios located on the planet's surface, and on the considerable social, economic and political disruption that radioactive elements can cause if they are used in the course of a terrorist attack.

In the fight against this very particular type of terrorism, the main actors on the international scene have been compelled to equip themselves with the best tools in order to adequately anticipate this threat and to fight it in the event that it finally manages to pass from power to act, and among these tools the nuclear forensics stands out for its usefulness and effectiveness, which mainly tries to locate the origin of the nuclear material that is eventually found outside the location where it should be kept or used.

2. Definitions

As a preliminary step to analyzing what nuclear forensics means and the importance it has acquired today, it is convenient to clarify the meaning of a series of terms that will appear relatively frequently in this article, in order to conveniently frame the development of the same. When the term nuclear forensics is used, and according to the International Atomic Energy Agency (IAEA), it refers to the "examination of nuclear material or other radioactive material, or of evidence that is contaminated with radionuclides, in the context of legal proceedings in accordance with international or national law related to nuclear security"(2015 a, p.1).With regard to nuclear security, there are two concepts that should be adequately differentiated, which are safety, defined as the "achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation risks" and security, defined as the "prevention and detection of, and response to, criminal or intentional unauthorized acts involving nuclear material, other radioactive material, associated facilities or associated activities" (IAEA, 2018 a, p.155). Regarding nuclear terrorism, which is the most worrying activity regarding nuclear and radioactive materials out of control, there are various possibilities available to organizations and individuals that have the purpose of committing attacks, and that are the manufacture of an Improvised Nuclear Device (IND), a Radiological Dispersal Device(RDD) and a Radiation Exposure Device (RED) (Ferguson and Potter, 2004).

The first of the options, manufacturing an IND, is the least likely but the most dangerous in case it comes to fruition, given the difficulty involved in the design of the weapon itself and the mandatory provision of the necessary materials for its use. In manufacturing, we must add the inevitable obtaining of the uranium or plutonium necessary for the nuclear explosion to take place, these materials are not available to the public, and they are normally stored in facilities equipped with the maximum security measures. The manufacture of an RDD is a more accessible possibility for terrorists, since in this case it is only necessary to commit the attack to obtain the radioactive material and attach a conventional explosive to it so that it can be dispersed once it has been placed on the designated target. Regarding the third of the options, the manufacture of a RED, it should be noted that it is the option that has greater facilities in its execution, since it is only necessary to conveniently locate a radioactive source in the vicinity of the target so that it is affected by radiation, this being much more dangerous in the event that the source in question is emitting gamma radiation, since it is endowed with a greater range and power to penetrate the matter than alpha and beta radiation.

Regarding the first option, manufacturing an IND, there are no documented cases in which they have been used, although it is true that some terrorist organizations, as was the case with Al Qaeda at the time, have tried to obtain it and vehemently expressed his interest in its use to spread terror, also judging by specialists that this possibility was real, as can be seen from a 2005 US report on weapons of mass destruction (The Commission on the Intelligence Capabilities of the United States, 2005). Regarding the manufacture of an RDD, there is evidence of several events, among them the one that occurred in Chechnya, on December 29, 1998, within the framework of the confrontation between the Chechen separatist forces and the Russian Government, and in which it was found a container with radioactive elements to which a mine had been attached, being avoided the explosion through the timely deactivation of the device (Nuclear Threat Initiative, n.d.).

There are also well-documented cases in which the use of a RED is involved. One of these, for its effects, was that of the Chinese scientist Gu Tianming, convicted in 2003 for being the author of the placement of several samples of radioactive iridium 192 in the workstation of a colleague in a Guangzhou hospital, with whom he was at odds. Several numerous people who passed through this facility were also affected by the radiation emitted (Nature, 2003).

It is also mandatory to refer to the regulations and to existing national and international treaties and strategies as means for the fight against nuclear and radiological terrorism. In this sense, the decisive action of the IAEA stands out, with the approval of the Convention on the physical protection of nuclear materials, which entered into force on February 8, 1987, in which the commitments acquired by the signer States are detailed, in order to prevent sensitive materials from falling into the wrong hands. It is also worth highlighting various resolutions of the United Nations Security Council, such as 1373, approved on September 28, 2001, which expressed concern about the link between international terrorism and the trafficking of, between others, nuclear materials, or 1540, approved on April 28, 2004, which appealed to the different States not to support non-State agents who had the intention of proceeding to the production of nuclear weapons or their vectors, urging them at the same time to establish measures to prevent the proliferation of these weapons. Finally, the United Nations General Assembly has also been significant in this regard, mainly through the approval of the aforementioned International Convention for the Suppression of Acts of Nuclear Terrorism, which entered into force on July 7, 2007.

It should also be mentioned that matters relating to nuclear and radiological materials or weapons are often included in the concept of CBRN, which also includes biological and chemical weapons. Regarding biological weapons, the greatest effort to combat them has been the approval of the Convention on Biological Weapons, in force since March 26, 1975 (Cuadrado, 2012), and with regard to chemical weapons, mention should be made of the work carried out within the framework of the Chemical Weapons Convention, which entered into force on April 29, 1997 (Organisation for the Prohibition of Chemical Weapons, 2021).

3. Origins

The foundation of nuclear forensics can be located in 1996, thanks to an initiative of the G-8 through which the Nuclear Forensics International Technical Working Group (ITWG) is instituted, in order to bring together a group of experts from various fields that could provide information and knowledge in forensic science, as a response to the trafficking of nuclear and radioactive materials (IAEA, 2006, p.1). The work of this group focused, fundamentally, both on the forensic analysis of nuclear and radioactive materials and on other evidence that could be contaminated with these materials.

The fundamental motivation for the creation of this group arose from the large amount of nuclear and radioactive material found since the beginning of the nineties outside the places where it had to be guarded, which was interpreted as an accurate indicator of the increase in activities of illegal traffic of these materials, and in the peremptory need to have a common procedure in the international sphere that would allow to find out their origin, in order to be able to attribute the corresponding responsibility. Among those materials detected in the nineties stand out due to their volume and significance 1.5 kg of HEU (Highly Enriched Uranium) detected in 1992 in Russia, 4.5 kg of HEU also detected in Russia in 1993, 3 kg of HEU also in Russia and 400 g of plutonium found in Germany in 1994 (Bíró et al., 2010).

In this regard, it is necessary to add that the IAEA has maintained since 1995 the Incident and Trafficking Database (ITDB), which consists of a compilation of all incidents, reported by the authorities of the States participating in this initiative, related to illicit traffic, unauthorized activities and other events in which nuclear and radioactive elements out of control are involved. The latest data released by the ITDB on February 2020showed a worrying number of 3,686 incidents, of which 290 were related to illicit traffic or malicious use, 1,023 corresponded to incidents in which the absence of information did not allow the attribution to illicit trafficking actions and 2,373 incidents that were not related to illicit trafficking (IAEA, 2020), which allows an adequate impression to be formed on the ease with which these sensitive materials, which must be properly guarded by the danger that they involve their exposure or manipulation, they are precisely outside that necessary control.

In the development of the concept of nuclear forensics stands out for its importance the report *Model Action Plan for Nuclear Forensics and Nuclear Attribution*, by the Lawrence Livermore National Laboratory of the United States, detailing the principles that were to form the basis of this discipline and that, from that moment, will be part of subsequent IAEA reference publications on the subject (Kristo et al., 2004). As has already been stated, the objective of nuclear forensics is to attribute an origin to the nuclear or radioactive materials found within the illicit traffic, for which, and in the same report previously mentioned, they are proposed as instruments to apply the use of forensic analysis of nuclear samples, understanding of the radiochemical signatures of these products, understanding of environmental signatures in order to be able to differentiate them from those under investigation, a comprehensive knowledge of the methods used for the production of special nuclear materials such as uranium enriched to a level greater than 20% in the isotope U235 or plutonium with a content of less than 7% in the isotope Pu240, which are those that can be used as fuel in the manufacture of a nuclear weapon; a knowledge of the process by which nuclear weapons are developed and, finally, adequate information from intelligence sources and law enforcement agencies. Regarding the purpose of this article, the aforementioned report adds that the forensic analysis is carried out on the intercepted material, including their possible containers, in order to obtain clues from their physical and chemical characteristics that lead to the attribution of its origin, which, ultimately, must be conveniently made available to those levels in charge of decision-making at national and international levels, so that the appropriate measures are taken to avoid attacks and for security measures to be put in place to prevent sensitive material from being used illegally.

In 2006 the reference manual *Nuclear Forensics Support* was published, which largely included the aforementioned Model Action Plan for Nuclear Forensics and Nuclear Attribution, which was of great help for States to have a guide for the correct application of nuclear forensics, since it included all the measures that make up the action plan that must be carried out in the course of an investigation in which nuclear or radioactive material was found. These measures could be grouped into five categories, which are the response to the incident, the taking of samples and their conduction to the nuclear forensic laboratory, the nuclear forensic analysis, the traditional forensic analysis and, finally, the nuclear forensic interpretation (IAEA , 2006, p. 13).

An important milestone in the establishment of nuclear forensics was the one established at the time by the holding of nuclear security summits, an initiative derived from the speech of US President Barack Obama in Prague on April 5, 2009, in which he described the nuclear terrorism as "the most immediate and extreme threat to global security", announcing at the same time the holding of a global nuclear security summit that would take place in the United States (NSS, Nuclear Security Summit, 2016). They took place in 2010 in Washington, in Seoul in 2012, in The Hague in 2014 and the last one again in Washington in 2016. At the first of the summits, the work plan was published in which it was already stated that "Participating States will explore ways to work together to develop national capacities for nuclear forensics, such as the creation of national libraries and an international directory of points of contact, to facilitate and encourage cooperation between States in combating illicit nuclear trafficking , including relevant IAEA activities in this area"(NSS, 2010).

In the second of these summits can be highlighted the promotion of the creation by the States of the National Nuclear Forensics Library (NNFL), as a means of improving nuclear security through its use in determining the provenance of runaway nuclear and radioactive material (US Department of Homeland Security, 2012).

In essence, an NNFL must contain information on the nuclear and radioactive materials that are produced, stored or used in each of the States participating in the initiative, and it is also recommended that they contain samples of those same materials. The data in these libraries are the responsibility of the States, which do not have the obligation to share them, although the IAEA insistently advocates international collaboration in this regard, whenever possible.

Regarding the third of these summits, it is worth noting the emphasis placed on the development of appropriate curricula for professionals related to nuclear forensics. The need to stimulate international collaboration and the use of a common language that would serve as a nexus of understanding between the participating actors was also emphasized (NSS, 2014).

Finally, and with regard to the last of the summits, several of the participating countries signed a joint declaration on nuclear forensics, in which various commitments were acquired, such as to develop and maintain the experience acquired in this field through interdisciplinary training of forensic and nuclear scientists, the timely transfer of knowledge to the following promotions of actors involved in the development of this matter, or the facilitation of participation in the various training activities that could be carried out in the international arena (NSS, 2016).

As stated, the evolution of nuclear forensic investigation has taken place at a dizzying pace, with the appearance of a large number of initiatives and with the fundamental impulse of the IAEA in its role as a center for international cooperation and as supervisor of the application of technologies and the use of nuclear materials for peaceful purposes. The United States has also played an important role in this process, mainly thanks to the initiative of national security summits and thanks to its network of national laboratories that allow it to be at the forefront of the main advances in investigation and application of nuclear forensics. It is therefore time to analyze the current state of affairs, which will be carried out in the next section.

4. Current state

At the time of writing this study, September to November 2021, the implementation guide entitled *Nuclear Forensics in Support of Investigations*, published by the IAEA in 2015, is available and in force, which without being a binding instrument for States, it does constitute an effective means of helping them to meet their demanding obligations in matters related to nuclear security. This guide contains various changes of interest in relation to the aforementioned 2006publication, going on to define in a more detailed way the way in which a nuclear forensic investigation is to be proposed and developed, following the model of the action plan, as explained in the following lines.

It is convenient to start the drafting of this section by noting that nuclear forensics is not a tool that is used in isolation or exclusively, since it must be part of a more extensive and complex process in which it is incardinated in a coordinated manner, in such a way that it is in a position to offer the competent authorities timely intelligence as a means of helping them make correct decisions. In this sense, and once the occurrence of an incident is known in which the use of nuclear or radioactive materials is estimated to have occurred, the timely response is carried out with an operation in which the security forces and CBRN response units can collaborate. Once the material found at the scene is collected, it must be transported to the corresponding laboratory, taking the necessary security measures that prevent exposure to radiation of the acting personnel and the public that is eventually in its radius of action. At this point, and before carrying out the analysis of the material, it is mandatory to develop a forensic examination plan, which describes the requirements of the evidence that will be carried out in support of a possible criminal process. In addition, the investigation needs and standardized procedures for conducting traditional and nuclear forensic examinations must be considered. The development of a forensic analysis plan is also mandatory, in which the description of the types of analysis that will be carried out in accordance with the requirements of the investigation and sequencing of the analyzes that are related to nuclear or radioactive materials is carried out. Next, the forensic work is carried out in the laboratory in which a traditional analysis will be carried out together with the strictly nuclear one, from which the corresponding interpretations that lead to forensic conclusions will be derived, which should include the origin of the nuclear or radioactive material found and the possible use of it. Finally, this same publication recalls the obligation of States to have adequate response plans in the face of situations in which nuclear security is affected, also stressing the need for the aforementioned model of action plan to be firmly incorporated into them.

The importance that nuclear forensics has acquired can be seen after consulting the nuclear security guide *Establishing the Nuclear Security Infrastructure for a Nuclear Power Program*, which once again emphasizes the need for States that have a program nuclear energy companies develop and apply the necessary forensic tools and techniques to maintain their security, which ultimately redounds to the benefit of the rest of the States (IAEA, 2013).

And it is that international cooperation is vital in maintaining adequate nuclear security regimes in each of the States, as stated by the then IAEA Director General Yukiya Amano in the foreword to the aforementioned *Nuclear Forensics in Support of Investigations*. The importance of this tool is also cited in the resolution of the IAEA General Conference on General Security of September 15, 2015, in which it is recognized as an important element of nuclear security (IAEA, 2015 b).

Within this section it is necessary to emphasize the impulse by the IAEA to the creation in each of the States of the aforementioned NNFL, which must contain sufficient reference information to allow an adequate comparison of the evidences found in the course of an investigation, so that it can be used to determine their origin (IAEA, 2018 b). In this case, and in many others related to the security and control of nuclear and radioactive materials, the IAEA has the particularity of being able to function as an effective catalyst that fosters international collaboration so that the most developed countries are involved in the advancement process of those who are in the lower echelons of the generation and application of scientific and technological advances.

At present, the IAEA continues to strengthen the capacities of States in nuclear forensics by publishing reference manuals on the subject and updating existing ones, assisting States in strengthening legal frameworks and technical infrastructures, helping for the development of national capacities in this matter through courses, seminars and other training activities and, finally, in the organization of conferences and meetings focused on coordinating the efforts of the different actors on the international scene (ITWG, March 2021).

The open panorama for the evolution of nuclear forensics is manifestly spectacular, considering the exponential availability of means of analysis with the use of advanced software, the accelerated exchange of information that has generated the introduction of the Internet throughout the world, the unstoppable advance of science and, above all, the urgent need to be in a position to respond to the serious threat posed by nuclear and radiological terrorism. Precisely at the international conference *Advances in Nuclear Forensics: Countering the Evolving Threat of Nuclear and Other Radioactive Material out of Regulatory Control*, held in Vienna between 7 and 10 July 2014, four challenges were exposed that could not be overcome in the next five years if one wanted to be in a position to ensure control of nuclear and radioactive materials. These challenges were the continuous development of the human resources involved in nuclear forensic investigation, the investigation and promotion of new analytical tools and methods, the exhaustive examination around how to maintain technical capabilities in this discipline and, finally, achieve an international commitment within the strategic scope.

5. Main tools

The tools to be used in the course of a nuclear forensic investigation are varied and of a very different nature, and are also constantly evolving, as a consequence of the emergence and application of advances in technology and specialized software. The main tools can be grouped into three categories, which are massive elemental and isotopic analysis tools, imaging tools, and microanalysis tools (Kristo, 2020). The necessary application of the integrated tools within the traditional forensic investigation must also be considered, although they will not be detailed in this article as there is already an abundance of bibliography on this issue. The most characteristic tools in each of the aforementioned categories are exposed and detailed below.

It is necessary to consider in this section the reference guides published by the aforementioned ITWG, in which there is abundant conveniently updated information on the correct use of the tools used in nuclear forensics. In this sense, the ITWG continues to lead the promotion of this discipline, trying to provide a common approach that allows the adoption of uniform criteria and becoming involved in the development of application techniques in this field (ITWG, n.d.).

5.1 Mass elemental and isotopic analysis tools

The techniques framed in this section allow us to find out the composition of a given sample, considering the elements of the periodic table that appear in it as well as their isotopic representation in it. The most representative tools in this section are those listed below.

5.1.1 Radiometric techniques

The aim pursued by these techniques is to measure the type and intensity of radiation emitted by the radioactive elements present in the sample under analysis. Some elements are characterized by their instability, which leads to them experiencing a so-called radioactive decay, in which the nuclei of their atoms fracture, being able to emit radiation in the form of particles or energy, in order to reach a state of greater stability.

This emitted radiation can be of three types, called alpha, whose composition is that of a nucleus of the element helium; positive or negative beta, corresponding to positrons or electrons; and gamma, which is equivalent to high-energy photons (Office of the Assistant Secretary of Defense for NCB Defense Programs, 2011). Each radioactive element has a particular way of disintegrating, a sample of which is the type of radiation it emits, its intensity and the time it takes for half of a sample of that element to disintegrate, a concept known as the half-life. Precisely with the aid of devices that are capable of measuring the different types of radiation emitted by a study sample, its elemental and isotopic composition can be initially determined.

Alpha spectrometry tools are available for elements emitting alpha radiation, which are used mainly in the identification of isotopes of elements such as Pu238, Pu239, Pu240, U233, U234 and Am241. The devices designed to carry out alpha spectrometry consist of an ion implantation silicon detector that converts the energy of the alpha particles into a proportional electronic signal, which passes through a preamplifier and an amplifier until it reaches a multichannel analyzer and a computer that with the appropriate software offers and analyzes the spectrum of the emitted radiation (Aggarwal, 2016).

Regarding the beta radiation emitting elements, the tools used in their analysis use two fundamental techniques for their operation. The first is constituted by gas ionization detectors, in which the radiation emitted by the sample being analyzed passes through a volume of gas, causing ionization of the gas and generating a flow of electric current whose timely measurement allows identify the emitting elements. The second of the techniques is the one used in scintillation detectors, based on the photon emission property of some elements when receiving ionizing radiation, which are transformed into an electric current that can be measured and interpreted (Sawant et al., 2020). The techniques included in this section are not usually used exclusively, since the wide range of energy that characterizes beta radiation forces them to be combined with other types of analysis techniques, in order to confirm the results obtained.

With regard to the elements characterized by being emitters of gamma radiation, there are two of the most used tools. The first of these is the one used in scintillation detectors equipped with thallium-doped sodium iodide crystal, NaI(Tl), in which the radiation emitted by the sample interacts with the scintillating material of the crystal producing flashes of light that are converted into electrical impulses that can be subsequently measured (Chiozzi et al., 2000). The second of these tools corresponds to the use in detectors of a semiconductor element, fundamentally germanium, which at the time represented a great advance compared to the first, due to their greater resolution capacity (Gilmore, 2008).

5.1.2 Mass spectrometry

This technique is used to determine both the concentrations and the isotope ratios of the elements that make up a sample under study. The principle on which mass spectrometry is based is that of the generation of ions from the sample being examined and their subsequent separation according to their mass/charge ratio, thus being able to carry out a quantitative and qualitative analysis in which determine which are the existing isotopes in it (Gross, 2004). There are mainly two techniques, used in the course of a nuclear forensic investigation, and they are Thermal Ionization Mass Spectrometry (TIMS) and Inductively Coupled Plasma Mass Spectrometry (ICPMS).

Regarding the first of the two tools mentioned, the TIMS, is based on the evaporation of the sample to be analyzed, through heating, ionization and the subsequent separation of these ions based on their charge and mass. This tool is extremely useful in finding out the proportions of isotopes in nuclear fuels, such as uranium and plutonium, which can be used at various times in the nuclear fuel cycle to keep track of the precise composition of a sample. Its use is also especially relevant to determine the age of a sample thanks to the knowledge of the half-lives and the analysis of the elements and isotopes present in the sample under study (Aggarwal, 2016).

As for ICPMS, it is a very useful technique in the course of a nuclear forensic investigation, mainly due to its high precision in detecting the elemental composition of a sample, reaching levels of nanogram per liter or per gram, which makes it possible to attribute an origin to it by comparing the results obtained with those available in a NNFL. In this case, the sample under analysis has to be nebulized and transformed into an aerosol, which is transferred to a chamber containing argon plasma, then producing the desired generation of ions which, as in the previous case, are separated according to the relationship between mass and charge (Wilschefski&Baxter, 2019).

5.1.3 Chemical assay

The techniques in this category are of two types, chemical titration and coulometry, and their purpose is to determine the concentration of nuclear elements in the sample under examination. In the first of these techniques, the sample is reacted with a reagent until it reaches its characteristic end point, obtaining then the data of the amount of the element that has been consumed in that reaction.

In the second technique, the element in question is oxidized or reduced, measuring the number of electrons lost or gained to establish the amount of that element in the sample being analyzed (IAEA, 2015 a).

5.1.4 Radiochemistry

This tool is mainly used to facilitate the separation of radioactive isotopes found in the sample under examination and is based on the separation by chemical means of the elements that compose it according to their different properties. With these techniques and those previously exposed, an identification of the elements present in the material being analyzed can be carried out (IAEA, 2015 a).

5.2 Imaging tools

The imaging tools allow obtaining more information that helps in the characterization of the samples to be examined, using visual inspection and considering parameters of interest such as appearance, shape, texture and others. Optical microscopes and scanning electron microscopes can be used for more detailed analysis. Finally, the so-called auto radiography can be used, which employs the radiation emission of a study material to achieve a characteristic image of it, which together with the rest of the exposed techniques contributes to the accurate characterization of the materials (Parsons-Davis et al., 2018).

5.3 Microanalysis tools

This type of tools is used to carry out an inspection that identifies the constituent elements of a sample, once it is certain that it contains a variety of components (IAEA, 2015 a). The techniques that make up this category use X-ray emission, which allow an analysis of the particles that make up the sample, or secondary ion mass spectrometry (SIMS), which are fundamentally useful in the quantitative or semi-quantitative characterization of the elements of that sample (Keegan et al., 2016).

6. Analysis of an investigation

As an illustrative case of how to develop nuclear forensic investigation, it can be cited the one carried out in 2003 at the Institute for Transuranium Elements (ITU), based in Karlsruhe, which was part of the Joint Research Center of the European Commission (Wallenius et al., 2006). In this investigation, four samples of uranium presented in the form of tablets were transported for subsequent analysis at the center, similar in appearance to those used in the manufacture of fuel elements, which are used in nuclear power plants dedicated to the production of electricity.

The first step in this research was to describe the appearance and shape of the study samples, using for this the help of an optical microscope that allows knowing the type of material, and obtaining the weights and measures. These data are necessary to be able to carry out a subsequent consultation in the available databases that allow to know the type of nuclear reactor in which they can be used. The next step consisted in carrying out an analysis of the sample using high-resolution gamma spectrometry, so that uranium could be identified as a component element of the sample. An analysis of the material was also carried out using specialized software, which gave as an initial result the enrichment of the uranium present in the sample in isotope 235, which was around 2%.

Next, techniques with greater precision were applied in order to achieve definitive results. These were mass spectrometry, through which the isotopic composition of the sample and the 2% enrichment in the U235 isotope could be confirmed, and three more techniques, which were potentiometric titration, uranium and plutonium concentration determination software(Hybrid K-egdeDensitiometry, HKED) and isotopic dilution mass spectrometry, which yielded data on the amount of uranium present in the sample, and which coincided with uranium dioxide, a component of pellets used as nuclear fuel. Another relevant test was the one concerning the identification of the impurities found in the sample, carried out by using the ICPMS, which allowed quantitatively ascertaining the elements present in it. By determining the impurities, clues to the production process of the sample material can be obtained, which can be helpful in identifying the location of its origin. The test that was developed next sought to determine the age of the sample, in order to know when it had been manufactured. For this, the radioactive decay of the uranium isotopes present in the sample and the knowledge of their half-lives were considered, which, through the application of various formulas, allowed the year 1990 to be assigned as the probable date of manufacture.

Carrying out these tests, with their corresponding results, together with the timely consultation of the ITU database on nuclear fuel manufacturers, made it possible to identify the type of nuclear reactor in which the fuel pellets being investigated were used, and that in this case it corresponded to a reactor of the type RBMK-1500 (Reaktor Bolshoy Moshchnosty Kanalny, high power channel reactor) cooled by water, moderated by graphite and designed and built at the time in the Soviet Union, which is only found in the Ignalina nuclear power plant, in Lithuania.

The fuel used in the aforementioned plant was manufactured by the Russian company MZ ELECTROSTAL, which made it possible to determine the origin of the study samples. A final consultation with the ITDB revealed that in 1992 various amounts of nuclear fuel had been stolen from the Ignalina plant. This circumstance, together with the information generated in the course of the investigation, made it possible to definitively conclude that the samples analyzed in the course of this investigation belonged to this case in an undisputed manner.

This is a sample of the way to carry out a nuclear forensic investigation in which most of the tools previously described take part and that, without a doubt, constitutes a clear example of the importance and interest that it has as a fundamental piece of application in the fight against terrorism in the specific field of the use of nuclear and radioactive materials.

7. Conclusions

It can be concluded that the terrorist threat through the use of nuclear and radioactive materials is possible and real, which makes it have a leading role in the security strategies of the main actors in the international community. It is true that this threat has not been able to manifest itself in a significant way, but the possibility of an attack with materials of these characteristics must be considered, especially if the availability of radioactive sources out of control and the enormous negative consequences that its use in the course of a terrorist attack would have for the normal development of social and economic activity is considered.

Among the tools developed to deal with this threat, nuclear forensics, the main object of the attention of this article, deserves to be mentioned. This discipline has been generously promoted from the international arena, mainly thanks to the efforts of the IAEA, so that it is currently established within the set of tools that law enforcement agencies have at their disposal for maintaining security around nuclear and radioactive materials. In addition, great efforts are being made by all the actors involved so that its use is extended in all those countries that have a nuclear program.

It is necessary to highlight the list of techniques that nuclear forensics uses to carry out its purposes. For this, it uses and integrates tools generated in different fields that end up characterizing this discipline in a decisive way. This also means that it is constantly evolving and that it requires a cooperative effort between the international actors involved and the support of organizations such as the IAEA and the ITWG, which have been especially significant for their interest and promotion of the discipline.

As has already been detailed in the preceding pages, nuclear forensics is currently in a state that ensures its relevance and interest as a fundamental tool in the network dedicated to the fight against terrorism. This is a struggle in which it is necessary to count on the collaboration of various agents and the support of institutions and States if the final result to be achieved is to ensure the well-being and peace of societies. Thus, this discipline is shown as an example of international cooperation and interdisciplinary effort, in which obtaining results shows the way in which the international community must act if it wants to be in a position to face a threat that it is willing to cause the greatest harm with the use of whatever resource it finds available.

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