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Nuclear forensics: How science helps stop the trafficking of nuclear materials

Gary R. Eppich

ABSTRACT

Nuclear forensics is an essential activity in support of national counter-nuclear smuggling operations, as it can be used to provide unique and useful data to law enforcement for the prosecution of criminal nuclear smugglers and traffickers. Nuclear forensics can also be used to determine the origin of nuclear materials that have fallen out of regulatory control, allowing for the identification of weaknesses and vulnerabilities in the safeguarding of nuclear materials, while also generating a deterrent effect through attribution to the legal and responsible owners of nuclear materials out of regulatory control. This article describes the benefits of a nuclear forensics capability to any country in possession of nuclear materials and describes how nuclear forensics can support an investigation into the origin of interdicted nuclear materials, using a case study of a nuclear materials interdiction in Australia to describe how nuclear forensics works in practice.

KEYWORDS

Nuclear forensics; uranium; plutonium; counter-nuclear smuggling; nuclear terrorism

On April 1, 2009, during a series of raids of clandestine methamphetamine laboratories in Melbourne, Australia, police made a disturbing discovery. Alongside the expected repositories of chemical reagents, guns, cash, and of course, copious amounts of illegal drugs, law enforcement agents stumbled upon an even more nefarious material: uranium (Roberts 2009).

In its highly enriched form, uranium is the essential component of a nuclear weapon, capable of killing millions. Naturally, it is illegal to possess uranium or other radioactive materials out of governmental control or in other highly regulated environments (such as hospitals and research laboratories) in Australia, as it is in most parts of the world. And yet, somehow these criminal drug manufacturers were able to get their hands on approximately 300 grams of uranium oxide, which they stored in two separate containers, neither particularly well protected.

The uranium in both containers took the form of fine-grained powders; one was a bright yellow color, and the other was a dull greenish-gray. Uranium is not known to play a role in the methamphetamine production process, and the criminals were unwilling or unable to explain why they possessed these hazardous materials, or where they came from.

There was no immediate indication at the scene of the crime as to whether the uranium was of the weaponizable, highly enriched variety, or of a more innocuous type. In response, the police called in radioactive materials specialists to deal with the unexpected mess. Responders outfitted with radioprotective gear were

able to safely secure the uranium and set it aside for analysis.

The discovery of uranium in criminal hands is, fortunately, a highly unusual occurrence in Australia, and this incident resulted in an immediate inquiry from the Australian government (Ludlam 2009). In addition to the essential information of whether the seized uranium powders were highly enriched or not, the Australian government wanted to know if the uranium had an origin within Australia, or if it came from somewhere else. If criminal drug traffickers in a relatively secure country like Australia could obtain uranium for no apparent reason, how many more radioactive materials must be out on the black market, available for purchase by the highest bidder?

The scope of the problem

In an era when terrorist groups and other non-state actors have gained a perhaps unprecedented level of influence and control in some parts of the world, and when transnational organized crime syndicates are on the ascendance, stopping the illicit trade of nuclear material has never been more critical. Terrorist groups such as the Islamic State of Iraq and the Levant, Al Qaeda, and others have stated openly their desire to obtain nuclear material for the construction of explosive devices capable of killing and injuring scores of people (Korbatov, Suzuki, and Goldblum 2015).

The global stockpile of what is called special nuclear material – a class of nuclear materials including highly enriched uranium and plutonium, the fissile materials

used in nuclear weapons – has not decreased in any meaningful way since their production began *en masse* in the 1940s. Compounding the threat, highly radioactive materials routinely used in essential civilian activities, such as radioactive therapy equipment often found in hospitals, are vulnerable to loss and theft. Well-documented incidents of nuclear smuggling and trafficking have taken place with regularity since the fall of the Soviet Union in the early 1990s (see Figure 1), and while the frequency of such incidents has declined somewhat in recent years, the threat has not dissipated completely.

It is unknown how many kilograms of uranium, plutonium, and other radioactive materials have escaped governmental control since the dawn of the Atomic Age, and it is likely that the cases shown here represent a mere fraction of the total. Even a single loss incident of radioactive or nuclear material has the potential to create a catastrophe, should the material end up in the wrong hands (Bentz, Blumenthal, and Potter 2014).

There are effectively two pathways for a malicious non-state actor to cause destruction with illegally acquired nuclear materials. The more likely but less catastrophic route involves the construction of a conventional explosive device paired with radioactive material, such as a cobalt 60 sealed radioactive source stolen from a hospital, for example. This type of improvised explosive is usually referred to as a radiological dispersal device because its purpose is not to produce nuclear yield, but to widely disperse radioactivity around

the immediate environment. If detonated in an urban area, such a device would likely only kill those unfortunate enough to get caught up in the conventional explosive blast. However, the dispersion of radioactivity in the immediate environment would cause mass chaos, rendering several city blocks uninhabitable for weeks or months, depending on the type of the radioactive isotope dispersed and the extent of its dispersal. Most people have an understandable fear of radioactivity, and the explosion of a radiological dispersal device would certainly cause people to flee, which could result in mass displacement and hundreds if not thousands of radiation exposures. While the radioactivity would dissipate rapidly with time, those who remain exposed to it would be at higher risk for various cancers, to say nothing of the trauma and mental health effects.

The second pathway, less likely but also almost unthinkable in consequence, involves the construction of an improvised nuclear device using stolen or otherwise illegally acquired nuclear material; either highly enriched uranium or plutonium would do. Although the construction of an operable improvised nuclear device is a far from trivial task, the detonation of such a device would potentially kill hundreds of thousands and maim millions more if detonated in a city. Such an event could have massive collateral effects as well, such as the collapse of a national economy, in addition to the fear and terror struck in the population at large. The detonation of an

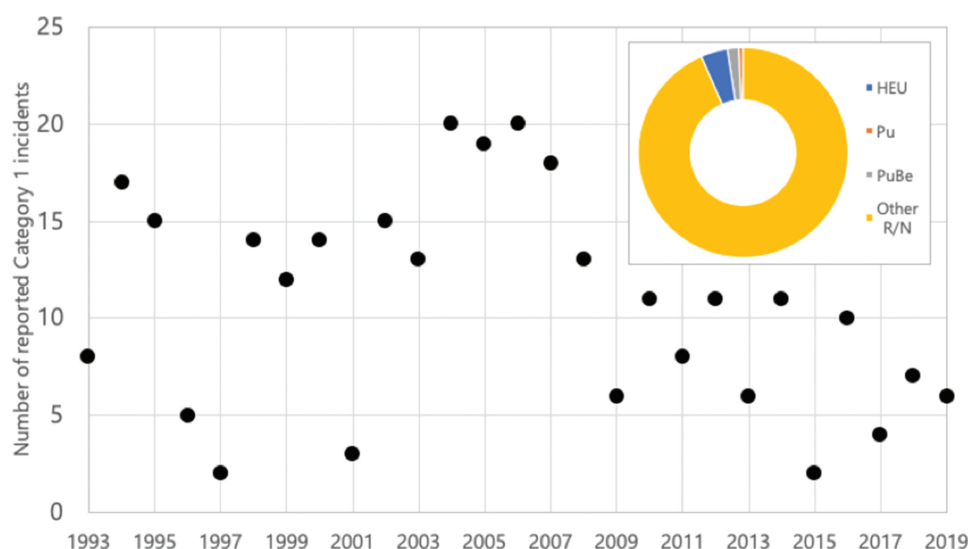


Figure 1. Nuclear smuggling and trafficking incidents reported to the International atomic energy agency between 1993 and 2019 that are known to be, or likely are, connected to trafficking or malicious use of nuclear materials (totaling 290 incidents since 1993). The inset sunburst plot shows a breakdown of the types of materials involved in these incidents; incidents include highly enriched uranium (12), plutonium (2), plutonium-beryllium neutron (“PuBe”) sources (5), and other radiological/nuclear (“R/N”) materials (271). All data are from the International Atomic Energy Agency incident tracking database (International Atomic Energy Agency 2020).

improvised nuclear device is truly the sum of all fears, and efforts to counter nuclear smuggling must be geared to prevent this from ever happening anywhere in the world (Tilden and Boyd 2020).

The most effective way to counter the threat posed by these two kinds of devices is to prevent nuclear materials from ending up in the wrong hands in the first place, by ensuring their continued protection in the hands of national governments.

The ability to credibly determine the origin of interdicted nuclear materials is a powerful deterrent to the countries that function as the stewards of these materials. Although non-state actors may not be deterred by an attribution capability (and may in fact want credit for committing such acts), if credible and reliable mechanisms exist for determining the origin of nuclear materials out of governmental control (or, at the very least, the ability to rule out possible origins), countries that have stated their commitment to safeguarding and securing their nuclear holdings (that is, all of them) can be held accountable by the international community for these lapses, and nuclear proliferation pathways can be identified and closed.

As a result, there is a continuing need for every country that possesses nuclear materials to develop a robust capability to analyze the physical, chemical, and isotopic properties of nuclear materials found outside of governmental control, a practice known as nuclear forensics. A national nuclear forensics capability can be beneficial in two principal ways: in providing legally defensible data to law enforcement in support of the prosecution and conviction of nuclear smugglers and traffickers; and in determining the origin of the interdicted nuclear materials so that further action can be taken to prevent future incidents (Mayer 2013).

Supporting law enforcement with nuclear forensics

The first goal of nuclear forensics is to produce information that is useful to legal authorities, providing them with technical conclusions that enable the enforcement of laws and regulations that prohibit the possession, transfer, or use of nuclear materials encountered outside of regulatory control. Every country has its own set of laws and regulations strictly controlling the use of nuclear materials. In some countries, these laws are weak and difficult to enforce, and definitions of what is considered a nuclear material may vary. In other countries, the regulations controlling the possession and use of

nuclear materials are well defined. For example, the United States federal code 18 USC § 831 states:

(1) the term “nuclear material” means material containing any – (A) plutonium; (B) uranium not in the form of ore or ore residue that contains the mixture of isotopes as occurring in nature; (C) enriched uranium, defined as uranium that contains the isotope 233 or 235 or both in such amount that the abundance ratio of the sum of those isotopes to the isotope 238 is greater than the ratio of the isotope 235 to the isotope 238 occurring in nature; or (D) uranium 233.

To determine whether a legal statute has been violated in the United States following this definition, the investigatory authority would have to be able to determine whether the interdicted material does, in fact, contain plutonium (which is not a naturally occurring element),¹ uranium 233 (also not naturally occurring), or uranium that has been enriched above the constant ratio of virtually all natural uranium on Earth.² If the material has an anthropogenically enriched ratio of uranium 235 to uranium 238, how precise must the measurement be to show this, to the satisfaction of a court of law? Or, if the material is determined to contain plutonium, how much of this element must be present to constitute a legal violation?

There are a number of tools that the investigatory authority could use to answer these specific questions, with varying degrees of precision. Field-deployable tools tend to sacrifice precision for portability, making them excellent choices for detecting and tentatively confirming the presence and abundance of isotopes like uranium 235 and plutonium 239 at a crime scene. However, field-portable tools are often not capable of producing the type of high-confidence data necessary to withstand cross-examination in the courts.

More precise tools are found in laboratory settings. For example, the US Department of Energy takes advantage of the unique capabilities of its network of national laboratories, such as Lawrence Livermore National Laboratory, located in California. Scientists from these laboratories use advanced analytical instrumentation to examine nuclear materials with high accuracy and precision, and their measurements are used to reach conclusions in support of investigations (Moody, Hutcheon, and Grant 2005).

Many other countries around the world have developed or are in the process of developing their own nuclear forensics capabilities, often in partnership with the United States. Laboratory analytical capabilities are routinely put through their paces during a series of biennial exercises (called the Collaborative Material Exercises and run by a global community of nuclear

forensics practitioners known as the Nuclear Forensics International Technical Working Group), during which nuclear forensics laboratories around the world work independently to perform rapid and thorough examinations of a nuclear material of which the origin is unknown to the participants, but known to the organizers.

Nuclear forensics laboratories typically follow International Atomic Energy Agency guidance on conducting nuclear forensic analyses of interdicted nuclear materials (International Atomic Energy Agency 2015). Many analytical techniques applied to nuclear forensic analysis can be performed rapidly, within minutes to hours upon receipt by the laboratory. For example, gamma spectrometry analysis, which takes advantage of the gamma radiation inherently produced by most radioactive isotopes, can provide high-precision data on which radioactive isotopes are present in a matter of minutes. Scanning electron microscopy analysis, used to take highly detailed images of a nuclear material to a scale as small as several thousandths of a millimeter, can be performed in a matter of hours. The chemical composition of a nuclear material sample can be quantified to a high degree of accuracy and precision using X-ray instrumentation on the same day that the material arrives in the laboratory.

Nuclear forensics laboratories are advised by the International Atomic Energy Agency to produce a report to legal authorities within 24 hours of receipt of the material in the laboratory. These data can then be used by investigators to answer key questions they may have about the material, such as its level of radioactivity and its isotopic enrichment. A national nuclear forensics capability provides investigators with the information they require to help determine rapidly and confidently whether legal statutes have been violated in the possession and use of the interdicted materials, as well as the degree of threat the materials pose.

Of course, the arrest and conviction of criminal smugglers and traffickers does not address the root problem, which is the unwillingness or inability of countries to adequately safeguard their nuclear materials from loss or theft. Without a robust nuclear forensics capability, the origin of interdicted nuclear materials may remain a mystery. To solve this mystery, investigators must be able to answer these two questions: Does this nuclear material come from our country? And, if not, where did it come from?

Determining the origin of lost and stolen nuclear materials

The second goal of nuclear forensics is to help determine the origin of smuggled and trafficked nuclear

materials so that further action can be taken. To this end, investigators can take full advantage of the spectrum of tools available, from “traditional” forensic analyses (fingerprints, hair follicles, cloth fibers, and other forms of trace evidence) to tools designed to interrogate the distinctive properties of nuclear materials. Criminal forensic laboratories are rarely equipped to perform measurements of the physical, chemical, or isotopic properties of nuclear materials, and almost certainly will not have the radioprotective equipment to ensure that the forensic scientists are not exposed to harmful levels of radioactivity. Therefore, investigators must establish partnerships with the types of laboratories that specialize in the measurement of these idiosyncratic pieces of evidence.

Inherent in any nuclear material is a set of materials signatures, characteristics indicative of where, how, and when it was made. Nuclear materials signatures are measurable properties, and they include color, size, and shape; enrichment level; trace elemental impurities; and the presence and abundance of fission products (Kristo et al. 2016).

All of these can help indicate the origin and history of the material. It is even possible in some cases to determine the date on which the nuclear material was produced using a method known as radiochronometry, or age-dating. In some cases, the nuclear material production date can be determined with an extremely high degree of precision, within days to months.³

Every interdicted nuclear material is likely to have several discriminating characteristics and, therefore, the relevant set of materials signatures to focus on will assuredly vary from material to material. For example, in the case of uranium fuel pellets, the physical form (diameter, shape, size, and density) is a key signature, because fuel pellets are manufactured to meet the narrow specifications of a specific make and model of nuclear reactor, and these data can therefore be leveraged to determine the type of reactor for which they were intended. In the case of certain types of nuclear fuels, the particular mix of actinide isotopes, fission products, and activation products is, in many cases, diagnostic of the type of nuclear reactor from which it came.

The raw materials used to make nuclear materials, such as uranium ores and uranium ore concentrates (often referred to colloquially as yellowcake, although they are not always yellow in color) very often have characteristic elemental compositions and isotope ratios reflective of geological origin, and a precise determination of the concentration of specific elemental impurities may be used for locating the geographic origin.

However, it is important to note that, because the global means of nuclear materials production are not necessarily unique to a country or to a specific facility within that country, a nuclear material's set of characteristic signatures may not always be unique, and it may not always be possible to identify its exact origin.

Laboratory analysts take advantage of the distinctive properties of nuclear materials to formulate conclusions regarding material origin, or to rule out possible origins. Because nuclear smuggling is a transnational problem, it is possible that a particular nuclear material may have an origin outside of the country in which the interdiction occurred. Many countries have developed a database of the signatures of their own nuclear holdings (called a national nuclear forensic library), which can be queried in the event of a nuclear material interdiction. The creation of a national nuclear forensic library requires the same set of analytical tools and expertise used in nuclear materials investigations, in the same laboratories, so the development of a national nuclear forensic library greatly complements a nuclear forensics capability. An understanding of the types of nuclear fuel cycle activities that currently or formerly did occur within one's own country is also helpful. Nuclear forensics is an iterative process; initial measurements often lead to unexpected discoveries, informing follow-on analytical efforts and approaches. In the case of the 2009 Australian uranium interdiction, unexpected discoveries abounded.

Revisiting the 2009 uranium interdiction in Australia

The task of determining the nature and origin of the two uranium materials seized by the Australian police in 2009 was assigned to the expert team of nuclear forensics analysts at the Australian Nuclear Science and Technology Organization. Initial analysis using gamma spectrometry made it immediately clear that the uranium was not the kind that can be used to produce nuclear weapons, that is, the uranium was not highly enriched. As a result of the long-running partnership in nuclear security between Australia and the United States, the Australian Nuclear Science and Technology Organization sent samples of the two interdicted uranium materials to Lawrence Livermore National Laboratory, where an independent set of analyses was performed in the United States (more details about the results of this investigation can be found in Kristo et al. 2015).

Australia is the home of the world's largest uranium reserves and is the third largest producer of uranium for use in commercial nuclear power plants (all uranium is sold as exports, since Australia does

not have a nuclear power infrastructure of its own). In this light, the discovery of uranium outside of regulatory control in Australia might not seem terribly surprising. However, a forensic examination suggests that these two materials have origins outside of Australia.

The two materials were similar-looking uranium powders in some respects, but of starkly different colors (see Figure 2; hereafter, the yellow powder will be referred to as material #1, and the greenish-gray powder as material #2). In uranium materials, color is often indicative of specific chemical and molecular compositions. Material #1 was a bright yellow color, similar to the types of uranium ore concentrates that are the primary outputs of Australian uranium mines and mills. Material #2 was a darker, greenish-gray color, and contained more uranium per unit mass than material #1. Careful examination of the microstructure of the materials also suggested distinctly different origins; material #1 consisted of 5 to 100 micrometer-sized clusters of even tinier particles, while material #2 contained particles of angular, 0.5 to 10 micrometer-sized grains. Material #1 primarily consisted of a highly unusual uranium compound ($K_2(UO_2)_3O_4 \cdot 4H_2O$), while material #2 was a more common substance ($UO_3 \cdot 2H_2O$).

The uranium materials were unusual in several other key respects; the isotopic composition of uranium in both materials was not enriched, but in fact was depleted relative to that of naturally-occurring uranium (that is, both materials had a smaller proportion of uranium 235 to uranium 238 than would be found in nature). Depleted uranium is a common by-product of the uranium enrichment process (the process of concentrating the isotope uranium 235 relative to uranium 238 for use in nuclear power reactors and in nuclear weapons). Depleted uranium itself is not considered a high-threat material, as it cannot be weaponized in an improvised nuclear device. However, the presence of depleted uranium is indicative of a uranium enrichment process on an industrial scale, which has never occurred in Australia. Clearly, this uranium did not come from Australia.

Even more puzzling, the materials contained a number of isotopes that do not occur naturally, most notably uranium 236 and uranium 232. Non-naturally occurring isotopes are produced through irradiation in a nuclear reactor, and this discovery indicates that both materials must have experienced a neutron flux (that is, spent time in a nuclear reactor) at some point in their histories. However, strangely, other activation products and fission products that would be expected in irradiated uranium

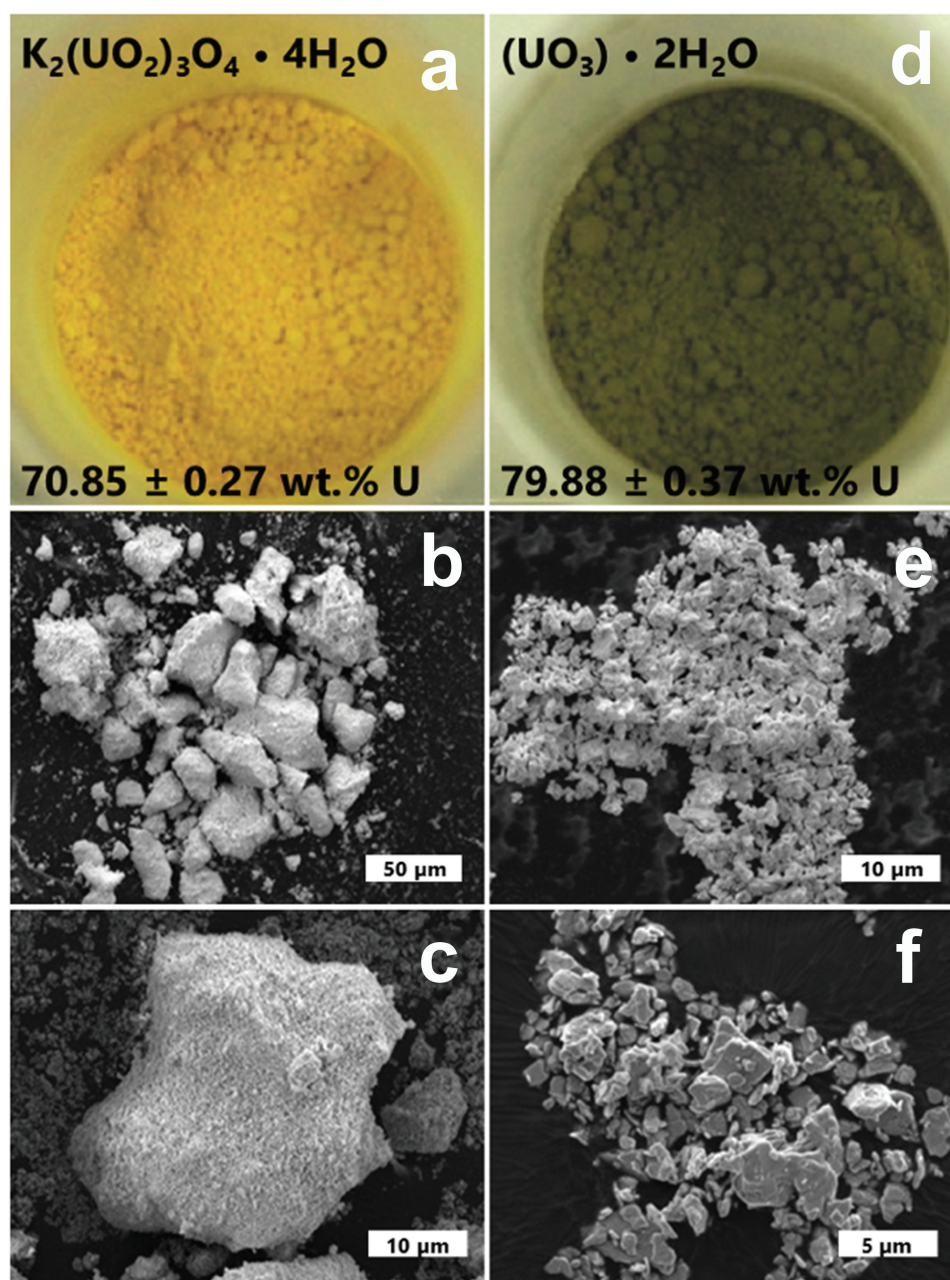


Figure 2. Results of physical characterization of the two uranium materials seized on April 1, 2009 in Melbourne, Australia. Panels A and D are photographs of uranium material #1 and #2, respectively. Panels B and C are scattered electron micrographs of uranium material #1; Panels E and F are scattered electron micrographs of uranium material #2. Chemical formulas were determined using X-ray diffraction; only the major phase is shown here. Uranium concentrations were determined using isotope dilution mass spectrometry, measured using a Nu Plasma MC-ICP-MS. Data are from Kristo et al. (2015).

materials, such as Cobalt 60, Cesium 137, and Europium 152, were not present. Moreover, uranium, when exposed to neutrons over time, undergoes a series of nuclear reactions that result in the production of plutonium; however, neither of these materials contained measurable quantities of plutonium.

The absence of plutonium, fission products, and activation products strongly suggests that these materials had undergone a process called reprocessing, which involves the chemical separation of the various highly radioactive constituents of nuclear materials after irradiation in a nuclear reactor. Because uranium 236 and uranium 232 are isotopes

of uranium, and therefore share identical chemical properties as other uranium isotopes, they would not be removed from the rest of the uranium during reprocessing. Since Australia is not known to ever have engaged in reprocessing activities, these findings again strongly suggest an origin of both materials outside of Australia.

Because these materials had almost definitely undergone an enrichment process and an irradiation process, it was possible to mathematically model both processes. Mathematical modeling of enrichment and of reactor irradiation processes can be useful for determining the types of nuclear fuel cycle facilities from which these materials could have acquired their unique signatures. Civilian nuclear fuel cycle activities must be declared to the International Atomic Energy Agency, and this information is available to investigators. The goal of enrichment and reactor modeling in the context of investigations is to model the effect that various nuclear processes would have on the isotopic composition of a nuclear material. Since different types of enrichment and irradiation processes impart different isotopic signatures on the materials they produce, it is in some cases possible to identify the type of facility from which these materials came (or at least rule out some possibilities, if a unique identification is not possible).

Identifying a unique match to these materials was challenging in this case, however, because the fission and activation products that would have been present were removed via reprocessing.

Despite the lack of complete information, it was still possible to demonstrate using well-established computer codes, used to simulate the effects of nuclear reactors, that the uranium isotopic compositions of these two materials were consistent with irradiation in a Russian-type high-power channel-type reactor (usually referred to as an RBMK reactor).

The RBMK reactor was a common type of reactor in the Soviet Union, although most have since been phased out of use, in part because of inherent and severe design flaws (the reactor responsible for the 1986 Chernobyl disaster was an RBMK reactor). The RBMK reactor can be used to produce weapons-grade plutonium, and reactor modeling is consistent with both materials having been used in the production of weapons-grade plutonium. The ratio of uranium 235 to uranium 238 in both materials is consistent with the type of enrichment cascade waste products known to have been produced by the Soviet Union, although other possible origins

cannot be completely ruled out in the case of either material.

It is important to note that it is highly likely that these uranium materials were transported to Australia for a legal purpose, later fell out of regulatory control, and that there was no malicious intent whatsoever by the former Soviet Union in the appearance of these materials in Australia. Depleted uranium has many regulated legal uses, and these low-threat materials were likely not intended for any nefarious purpose.

A pathway forward

This case demonstrates the transnational nature of nuclear smuggling and trafficking, and the critical role that nuclear forensics can play in addressing it. The ability to trace the origins of nuclear materials that have fallen out of governmental controls is an important arrow in the quiver for counter-nuclear smuggling operations. Nuclear forensic analysis can provide critical support to law enforcement and is a core constituent of the spectrum of capabilities used by nations to deter the smuggling and trafficking of nuclear materials in and through their countries. All countries should continue to develop their nuclear forensics capabilities to an extent commensurate with specific nuclear security concerns in their region. As nuclear smuggling and trafficking remains a transnational problem, nuclear security must remain a global effort, and continued partnerships in nuclear forensic analysis remain the cornerstone for effective and efficient countermeasures to the threat posed to humanity by lost or stolen nuclear materials falling into the hands of those who would do harm.

Notes

1. Although plutonium is generally considered a non-naturally occurring element, minute traces of plutonium can be found in certain environments, usually well below the limit of detection of even the most sensitive analytical instrumentation. Atoms of plutonium are produced naturally through rare nuclear reactions in uranium-rich materials. Also, anthropogenic plutonium has been introduced into the environment, primarily through above-ground nuclear weapons testing.
2. Uranium is a naturally occurring element, albeit with very low abundance in the Earth's crust, about 1 part per million on average. There are two major isotopes of uranium: uranium 238 and uranium 235. For naturally occurring things unadulterated by humans, the ratio of the uranium 235 isotope to the uranium 238 isotope is the same virtually everywhere: approximately 0.725 percent.

Uranium enrichment activities (and the resultant depleted uranium tails) have somewhat altered this ratio in areas of the world contaminated by enriched and depleted uranium, such as at the Nevada National Security Site, where the United States conducted nuclear weapons testing.

- 3.. Radiochronometry takes advantage of the relative abundance of parent-daughter nuclide pairs in uranium- and plutonium-rich nuclear materials to determine the “production age” of nuclear materials. The most commonly-used pairs include uranium 234–thorium 230, uranium 235–protactinium 231, and americium 241–plutonium 241; material age is calculated using known half-lives of each nuclide, and assuming that the daughter nuclide composition was zero at the time of production. This assumption is often true, but if untrue, it will result in ages older than the “true” material age. Use of multiple parent-daughter nuclide pairs increases confidence in calculated age when they agree.

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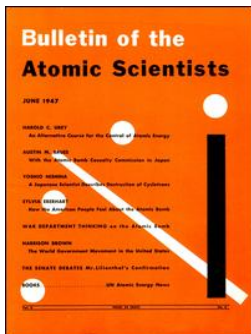
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nuclear nonproliferation for over a decade.

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