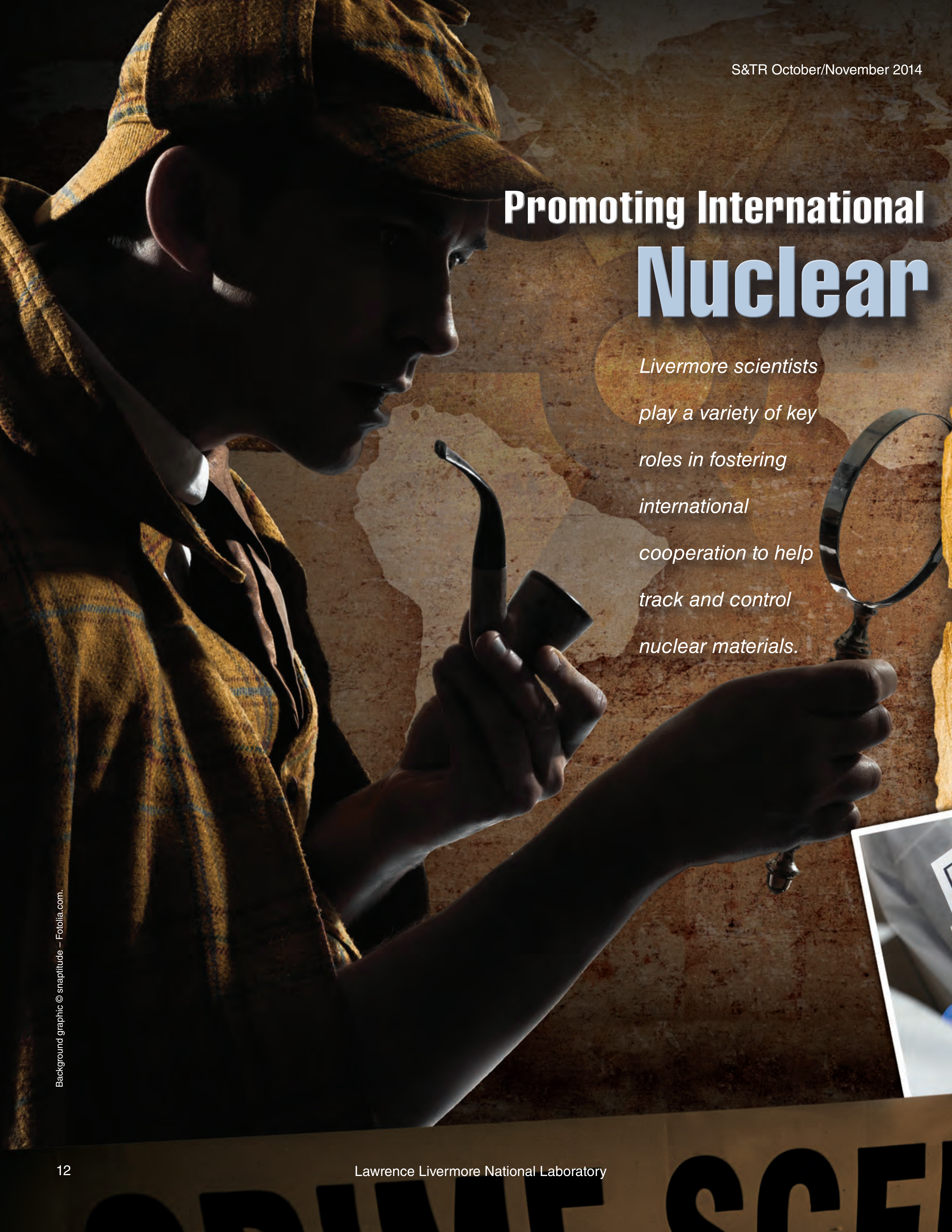

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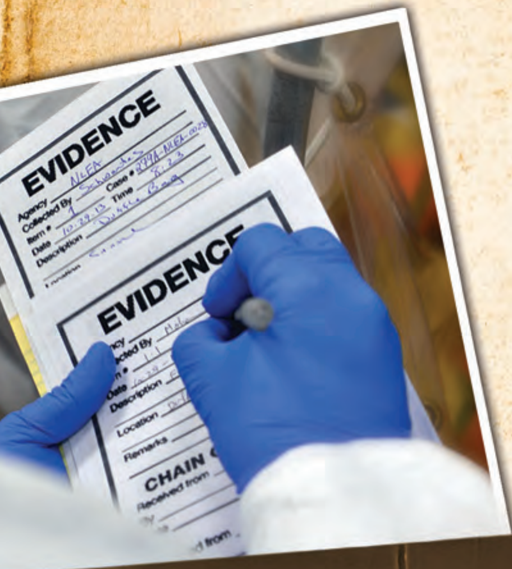
Promoting International Nuclear

Livermore scientists play a variety of key roles in fostering international cooperation to help track and control nuclear materials.

Security through Forensics

THE possibility of the smuggling and trafficking of radiological and nuclear materials has become a very real threat over the past 20 years. A major security concern of the international community is the activity of groups, whether nation-states or terrorists, seeking to obtain such materials for illicit purposes. To address this threat, several national and international endeavors seek to control the spread of nuclear materials as well as the technology and expertise associated with their production and use. In particular, the Office of Nonproliferation and International Security in the Department of Energy's (DOE's) National Nuclear Security Administration and the International Atomic Energy Agency (IAEA) work together to ensure that a system exists to identify the source of any interdicted materials.

Lawrence Livermore is an active participant in these efforts, bringing its many decades of expertise in nuclear weapons design and performance to the newer discipline of nuclear forensics. In nuclear forensics, investigators act as "sleuths," analyzing nuclear or radioactive materials for clues to a material's source to identify where legitimate, legal control was likely lost. An extensive team of Livermore scientists, including Martin Robel, Erick Ramon, and Naomi Marks, is engaged in a number of areas to promote international understanding and collaboration in nuclear forensics and to advance technical capabilities in the field. From building nuclear forensic tools "at home" to teaching good laboratory practices abroad, the Livermore team is engaged in a global undertaking to secure nuclear material and disrupt black market trade.



Nuclear forensics investigators act as sleuths, searching for evidence that will help them determine the history and source of nuclear or radioactive materials found outside regulatory controls. (Photo at left courtesy of Dean Calma/ International Atomic Energy Agency [IAEA].)

Bringing Insight to Databases

Over the last decade, Robel's development of the Uranium Sourcing Database and the innovative database query system DAVE (Discriminant Analysis and Verification Engine) has contributed significantly to the Laboratory's efforts to foster international cooperation in nuclear forensics. Robel first created DAVE to interrogate huge amounts of chemical information on yellowcake, a form of uranium used in the nuclear fuel cycle to make material suitable for enrichment. The information initially arrived on Robel's desk as a spreadsheet containing 34,000 data points for 1,700 samples of yellowcake. Robel used that information as the starting point for creating the Uranium Sourcing Database. The sophisticated database has been expanded to include data for uranium ore and uranium tetrafluoride, which are also materials involved in the early stages of the nuclear fuel cycle. The Uranium Sourcing Database now contains approximately 190,000 data points, representing more than 6,300 samples from 133 distinct sources and 31 different countries.

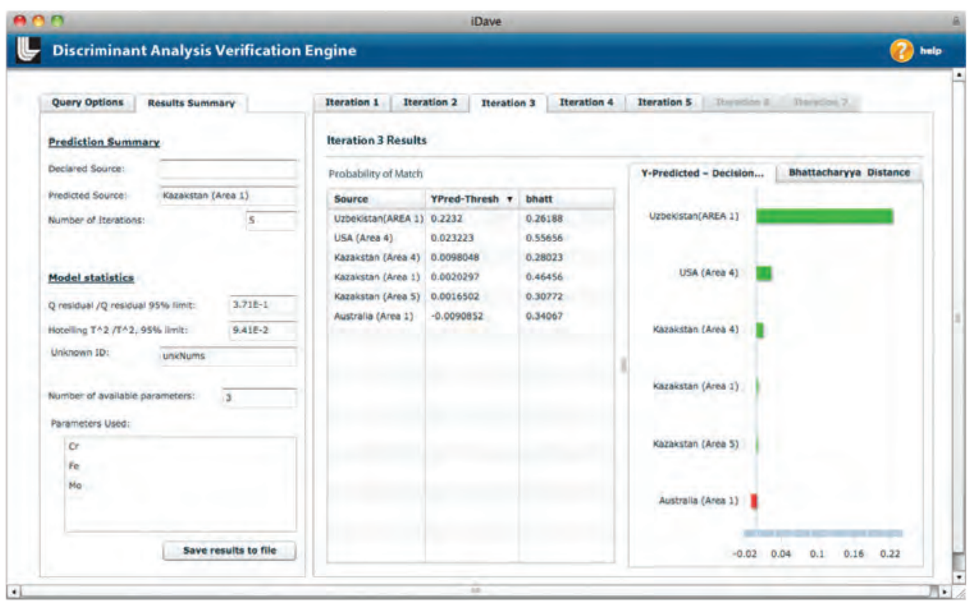
Each sample in the database is defined by 20 to 80 variables, including major and trace element abundances and certain isotope ratios. The number of variables for each sample depends on the organization that conducted the sample analysis and the composition of the sample. Robel explains, "When Livermore analyzes a sample for inclusion in the database, we focus on about 80 variables or criteria, looking for traces of most of the elements in the periodic table as well as making high-accuracy, high-precision, destructive analysis measurements." In contrast, most sample data submitted from outside organizations have been gathered for quality control and production purposes rather than for nuclear forensics. These analyses usually cover only 20 variables, and the measurements tend to be less precise.

Yellowcake, in particular, is of interest in the nuclear forensics arena for several reasons. First, it contains about 60 to 80 percent uranium, which can be separated into isotopes and enriched to make material suitable for a nuclear explosive device or weapon. Second, it is a commodity, legally traded in large volumes on a global scale. Third, unlike data on plutonium or highly enriched uranium, information about yellowcake is not sensitive, so the data can be used for collaborative research both domestically and internationally. Finally, yellowcake signatures—those distinguishing values or combination of values for a given sample's variables—are complex, reflecting both the original source ore and the ore's subsequent processing. "Unlike DNA samples, for instance, yellowcake samples do not have a unique 'fingerprint,'" says Robel. "Substantial variability exists in material from a particular source." This variability makes yellowcake a challenging case study for developing nuclear forensic analysis methods.

The Uranium Sourcing Database contains a wealth of information, but it is DAVE, Robel's innovative query system, that harnesses the database's potential. DAVE uses advanced statistical methods to quickly identify the most likely sources for an unknown sample. The query system incorporates partial least-squares discriminant analysis (PLS-DA), a powerful statistical method for discriminating between classes of samples (for example, samples from different uranium mines). It also incorporates MATLAB (matrix laboratory), a programming language for manipulating matrices and plotting functions and data. "When one has 70 variables per sample and 1,000 samples, things quickly get complicated trying to compare and discriminate between them," says Robel.

The PLS-DA algorithm eases the task of discriminating among sample classes by including a dimension reduction step. This step collapses multiple correlated variables into a few "latent variables," which are not measurable but can be mathematically inferred by the algorithm. Thus, a large number of observable variables can be aggregated in a model to represent an underlying concept, making it easier to understand the data.

At Livermore, Robel teamed up with Justin Shinn of the Technical Information Department and Greg White of the Global Security Principal Directorate to create and implement iDAVE, the



iDAVE, the Web-based discriminant analysis verification engine, created by Livermore researcher Martin Robel and web developer Justin Shinn, discriminates between dozens of yellowcake sources using an iterative process of elimination. iDAVE accepts a remote user's sample data and returns a predicted source and additional statistics.

Building international communities is key to creating a global, nuclear-secure future. Livermore scientists work with staff from the Nuclear Energy Corporation South Africa (NECSA) to help that country develop its own nuclear forensics laboratory. Here, Livermore researcher Rachel Lindvall (standing) trains NECSA staff on the use of inductively coupled plasma mass spectrometry, an analytic technique for identifying elements. (Photo courtesy of Christina Ramon.)

web application version of DAVE. The iDAVE website, which resides on a special network, allows authorized users to remotely query the Uranium Sourcing Database. iDAVE accepts a sample's data from a remote user, then quantitatively and statistically compares the data to those in the database, and finally, returns a prediction about the source of the unknown with additional statistics.

Livermore's Michael Kristo, associate program leader for Pre-Detonation Nuclear Forensics, notes, "One policy goal of the U.S. and IAEA with respect to nuclear forensics is to encourage the creation of national nuclear forensic libraries. What Robel has created is a fantastic example of what a nuclear forensic database could and should be."

The combination of the Uranium Sourcing Database and DAVE/iDAVE allows Livermore scientists and others to determine the origin of unknown materials sometimes seized on the other side of the globe by police or border security. As part of DOE's international outreach efforts in nuclear forensics, Robel and others involved in this project share the database structure, lessons learned, and the analysis algorithm used in DAVE. Armed with this information, individual countries can build country-specific databases and query systems, creating one of the key capabilities of their own nuclear forensics programs.

Developing Capabilities Abroad

For capabilities such as iDAVE to be most effective, nuclear forensics needs to be encouraged and supported in those areas of the world touched by nuclear trafficking and black market trade. Livermore staff members participate in bilateral engagements with countries such as Ukraine, Russia, France, Kazakhstan, Japan, China, Australia, Korea, and South Africa, helping each country develop the infrastructure and good laboratory practices required for a nuclear forensic facility. Lawrence Livermore is home to some of the world's foremost nuclear forensic experts, including Ian Hutcheon, Pat Grant, and Ken Moody. These three scientists literally wrote the book on nuclear forensics (*Nuclear Forensic Analysis*, the first primary reference source in the field). It is thus fitting for Livermore to be deeply engaged in this international effort to assist those countries interested in developing their own domestic capabilities.

Every country, Ramon notes, is different. "There isn't a one-size-fits-all blueprint for setting up a nuclear forensic capability," he says. "That's where the Laboratory comes in. We provide experts to answer questions, offer guidance and suggestions, and share tools and capabilities." Ramon participates in the South Africa engagement, which is aimed at developing that country's expertise in nuclear materials characterization. Ramon and Hutcheon, who is the Livermore lead for the engagement, provide assistance and advice with practical issues such as the setup and operation of laboratory facilities and equipment.

South Africa is an example of a country that has developed a credible nuclear forensic capability. Hutcheon explains that although South Africa abandoned its nuclear weapons program in the 1990s, the country retained an ongoing program in nuclear safeguards. After participating in the Nuclear Forensics International Technical Working Group meetings sponsored by the G8 countries (a group of eight highly industrialized nations), South Africa indicated its interest in developing a nuclear forensic capability. In 2011, Lawrence Livermore and Los Alamos national laboratories and the Nuclear Energy Corporation South Africa (NECSA) signed a memorandum of understanding that allowed Livermore and Los Alamos to provide ongoing support to South Africa through the state-owned NECSA.

NECSA performs research and development in nuclear energy and radiation sciences and is responsible for processing source material, including uranium enrichment, as well as cooperating with other institutions locally and globally on nuclear and related matters. “Through NECSA, South Africa came into this engagement with well-educated, outstanding scientists and a robust skill set,” says Ramon. For several years, Lawrence Livermore and NECSA have worked closely to build new forensic laboratories in Pretoria, South Africa, and train NECSA scientists in analysis methods. This training is critical to building an international network of sleuths who can compare results and track down nuclear material trafficking.

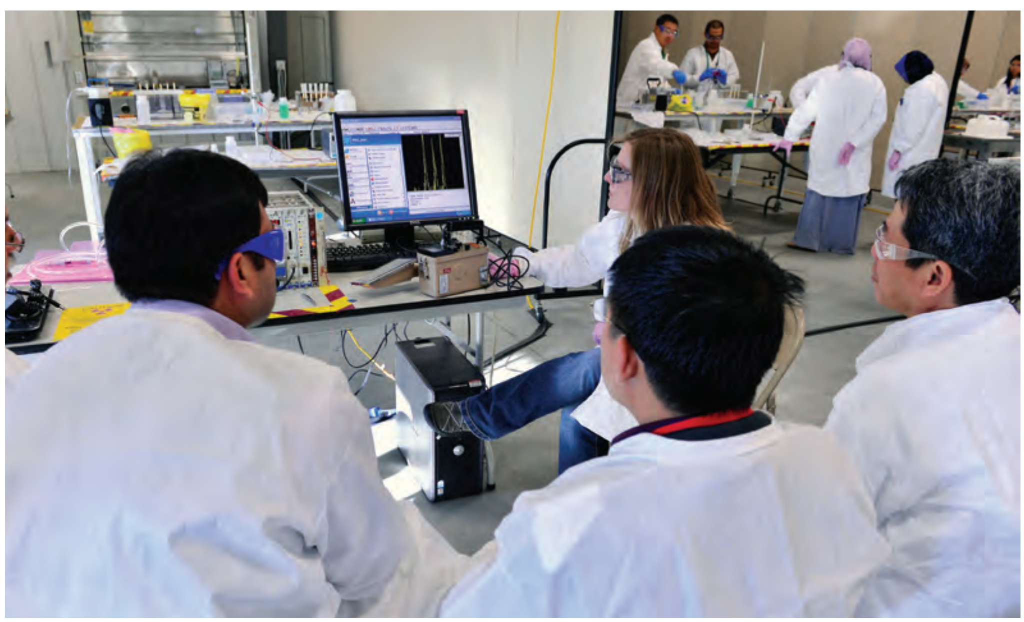
NECSA was able to test its capabilities under real conditions in December 2013, when police seized an unknown radioactive material in Durban, South Africa. “Because we had this memorandum in place, Livermore and NECSA could share aliquots of sample material and compare results of our parallel analysis,” explains Hutcheon. In July 2014, Lawrence Livermore and NECSA presented their joint findings in Vienna, Austria, at the IAEA International Conference on Advances in Nuclear Forensics: Countering the Evolving Threat of Nuclear and Other Radioactive Material out of Regulatory Control. Ramon says, “It’s a win–win situation for both countries, in that the U.S. would like to have regional partners whose analytical results we trust as much as our own.”

The International Classroom

One answer to the puzzle of how to bring international nuclear forensics to the world is bilateral engagements, and another is multilateral meetings. These events serve to bring the larger international community together to share information and continue training in state-of-the-art nuclear forensics. Marks is part of a DOE team of experts who meet annually to conduct the International Workshop on Nuclear Forensics Methodologies, which is hosted by Pacific Northwest National Laboratory at the Volpentest HAMMER Federal Training Center in Richland, Washington.

The joint DOE/IAEA two-week workshop trains representatives of member states in the methods of nuclear materials characterization. The workshop includes classroom and laboratory instruction on technical forensic investigations of nuclear security incidents. Participants are selected by IAEA from a pool of individuals nominated by their home countries. As Marks notes, “We have participants who come from law-enforcement agencies, the military, and utilities as well as from organizations such as the Pakistan Atomic Energy Commission. Some are well versed in the subject of nuclear chemistry or forensics, while others are not. So we start with the basics.”

The curriculum focuses on the role of scientists and lab technicians in analyzing



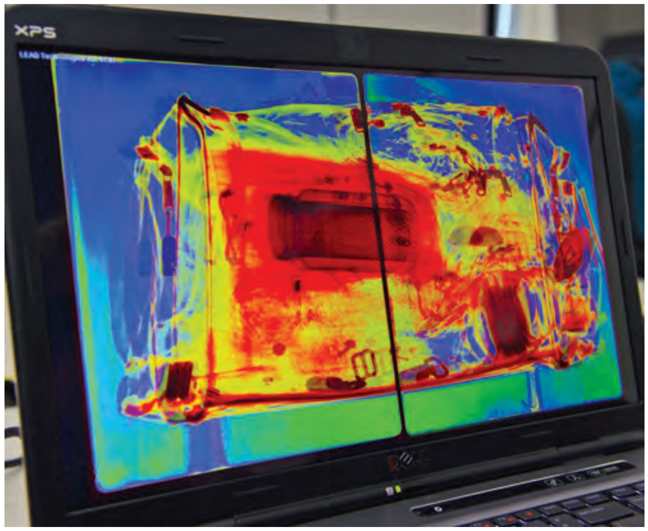
The National Nuclear Security Administration’s Office of Nonproliferation and International Security and IAEA cosponsored a second International Workshop on Nuclear Forensics Methodologies at Pacific Northwest National Laboratory in Richland, Washington, in the fall of 2013. The workshop included 26 participants representing 10 countries: Algeria, Bulgaria, Czech Republic, Indonesia, Malaysia, Mexico, Pakistan, Singapore, Thailand, and Vietnam. Participants learned all the steps in an investigation from collecting evidence to analyzing data. (Photo courtesy of Dean Calma/IAEA.)

nuclear and other radiological forensic evidence. Marks, who is instrumental in developing the course syllabus, explains that the curriculum is “scenario-based,” highly interactive, and includes hands-on exercises in a simulated forensic investigation of a nuclear material smuggling incident. “The participants role-play different characters throughout the scenario, beginning with a border guard, then a nuclear forensic lab worker, and finally, a national point of contact,” says Marks. “In this way, they learn what’s involved in every step of the nuclear forensic investigation.”

The scenario begins with real vehicles—from small passenger cars to large commercial semitrailers—driving through a transportation portal. Participants use handheld radiation detection devices to determine if the material the driver is carrying matches what is on the manifest. When they find something questionable, the students then plan and conduct an “investigation.” They use traditional and nuclear forensic techniques to determine if the conditions for a radiological crime scene exist. The participants are trained in the use of glove bags, radiological controls, and gamma spectrometry. They also learn how to prepare samples for alpha spectrometry. In addition, participants determine if their investigation would benefit from destructive analysis, including mass spectrometry. Throughout the investigation, participants gather data such as whether the material is radioactive, whether it is enriched, and what isotopes are present and in what amounts.

“We also talk about what a lab should look like, what equipment to include, and the infrastructure required,” says Marks. “At a minimum, one needs a clean space. After that, one can add alpha- and gamma-spectroscopy capabilities. Mass spectrometry is great, but pricey in many ways. A mass spectrometer can cost from $200,000 to several million dollars. One also needs a facility to house it, a large power source, and air-handling and temperature control systems. Finally, skilled people are needed to run the facility.”

As the course progresses, participants are given the opportunity to address the fundamental question in nuclear forensics: “Is this material, which is out of regulatory



At the hands-on fall 2013 workshop, participants learn traditional forensic techniques, such as how to identify hidden objects using gamma spectrometry and x-ray detection (shown here) methods, as well as more specialized nuclear forensic techniques. (Photo courtesy of Dean Calma/IAEA.)

Livermore scientist Naomi Marks describes some of the imaging techniques used in nuclear forensics at the fall 2013 workshop. (Photo courtesy of Dean Calma/IAEA.)

control, ours?” This final module examines the importance and use of national nuclear forensic libraries (also known as databases). Marks begins by introducing participants to the concept of a database. “Many participants come to the workshop with the idea a spreadsheet is a database,” she says. “However, in a database, one uses the data but cannot change the information.” In its most basic form, a database is similar to modular storage units in that it provides a structure that can be filled with whatever information is desired. Marks reviews the types of databases, from “flat” to those featuring sophisticated and complex means for assembling and querying data collections.

The participants use the data they have collected in the scenario to query an instructional database. Marks has populated this database with data from 5,000 samples, including medical isotopes, sealed sources, and yellowcake. The data are “synthetic,” that is, they look authentic but do not represent real samples. Students query the database using simple query strings to determine if the unknown samples match any of the nuclear material holdings of their imaginary country.

Teaching the course has its challenges and its rewards. “The biggest challenge,” says Marks, “is the language barrier. Although the workshop is taught in English, most of the participants speak English as a second, third, or fourth language. The language differences can lead to confusion. The biggest reward for me is helping people understand the importance of nuclear forensic databases and seeing them make giant leaps in understanding those databases.”

A Global Solution

As Kristo and Hutcheon both point out, the U.S. is not alone in its concerns about nuclear terrorism. In his first speech to the United Nations Security Council in 2010, U.S. President Barack Obama called nuclear terrorism “the single most important national security threat that we face.” The goal of the U.S. is to encourage “capacity building,” that is, improving the ability of other countries to conduct nuclear forensics and, at a minimum, be able to detect materials that are outside regulatory controls.

Building international communities is key to creating a nuclear-secure future. “These are international issues,” says Hutcheon, “and global engagement is essential to address the critical 21st-century problem of illicit tracking of nuclear materials.” Livermore is working many pieces of the problem, including offering expertise and advice to those interested in developing baseline capabilities in their own countries and building long-term trust and relationships that are key to meeting future national security challenges. Lawrence Livermore’s nuclear forensic experts share their knowledge through multilateral and bilateral efforts, workshops, database technology, and direct scientist-to-scientist interactions. Adds Hutcheon, “It’s only by working together and helping others to help themselves that we can hope to combat illicit tracking of nuclear materials on a global level.”

—Ann Parker

Key Words: International Atomic Energy Agency (IAEA), nuclear attribution, Nuclear Energy Corporation South Africa (NECSA), nuclear forensics, nuclear material, partial least-squares discriminate analysis (PLS-DA), uranium ore concentrate, Uranium Sourcing Database, yellowcake.

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