Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy.

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Nuclear Forensics Analysis Center:
Forensic Analysis to Data Interpretation

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Abstract

The Nuclear Forensics Analysis Center (NFAC) is part of Savannah River National Laboratory (SRNL) and is one of only two USG National Laboratories accredited to perform nuclear forensic analyses to the requirements of ISO 17025. SRNL NFAC is capable of analyzing nuclear and radiological samples from bulk material to ultra-trace samples. NFAC provides analytical support to the FBI's Radiological Evidence Examination Facility (REEF), which is located within SRNL. REEF gives the FBI the capability to perform traditional forensics on material that is radiological and/or is contaminated. SRNL is engaged in research and development efforts to improve the USG technical nuclear forensics capabilities. Research includes improving predictive signatures and developing a database containing comparative samples.

History and Background

The basic principles employed in nuclear forensics started with the first nuclear weapons test at Trinity. Those techniques were developed to determine yield, and later expanded to determine materials used, design details of nuclear explosions carried out by the US and latter by other countries. Next, the capability to measure and access risk was developed to monitor environmental concerns surrounding nuclear facilities. The advent of modern terrorism and the potential threat of nuclear or radiological dispersal device (RDD) increased the need to safeguard and develop the capability to identify where nuclear material was produced. The need for robust nuclear forensics to assist in attribution of nuclear material has become increasingly important as result of potential terrorist attacks.

The US government responded in a number of ways to handle this new threat, one of them was the creation of the Department of Nuclear Detection Office (DNDO). DNDO was established on April 15, 2005. Its mission is to "improve the Nation's [US] Capabilities to detect and report

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unauthorized attempts to import, possess, store, develop, or transport nuclear or radiological material for use against the Nation [US], and to further enhance this capability over time." [2] In October 2006 DNDO established the National Technical Nuclear Forensics Center (NTNFC) and charged it with two main goals. First, the NTNFC is to act at a national-level as a systems integrator for exercising, joint planning and evaluating national capabilities.[3] The second is to invest in technical capability advancement.[3]

March 24, 2009 the House of Representatives passed H.R. 730: Nuclear Forensics and Attribution Act, the Senate passed the bill on December 23, 2009 and President Obama signed the bill into law on February 16, 2010. The bill "establish[es], within the Domestic Nuclear Detection Office, the National Technical Nuclear Forensics Center to provide centralized stewardship, planning assessment, gap analysis, exercises, improvement, and integration for all Federal nuclear forensics and attribution activities."[4] H.R. 730 further recognizes the need to maintain expertise. It establishes undergraduate scholarships and graduate fellowships. The graduate fellowship includes a requirement, if possible, to spend at least two summers interning at a national laboratory or appropriate Federal agency and each fellow commits to serving two years in a post-doctoral position in a technical nuclear forensics-related specialty. Both the academic and the intern/post-doctoral work is to be performed in an area of technical nuclear forensics.

Savannah River Site (SRS) was constructed during the early 1950s to be a facility that primarily produced tritium and plutonium for US nuclear weapons. At its height SRS was operating five heavy water production reactors, two separation canyons, fuel fabrication, tritium facility, a heavy water production plant, along with laboratories that supported site missions. Savannah River Laboratory supported the missions of SRS and provided environmental monitoring. In 2004 Savannah River Laboratory was designated a national laboratory under the Department of Energy (DOE) office of environmental management. The Nuclear Forensics Analysis Center (NFAC) resides in the Non-proliferation Technologies Section (NTS) which is involved in supporting non-proliferation activities and conducting research and development to improve or create new methods used in non-proliferation work.

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[2] Department of Homeland Security web site, "Domestic Nuclear Detection Office", Accessed on December 7, 2010, http://www.dhs.gov/xabout/structure/editorial_0766.shtm

[3] *The Domestic Nuclear Detection Office: Can It Overcome Past Problems and Chart a New Direction?*, Opening statement of Warren M. Stern, Director of DNDO, September 30, 2010.

[4] H.R. 730, Nuclear Forensics and Attribution Act

NFAC employs expertise in chemistry, physics, engineering, oceanography, meteorology, nuclear engineering, biology, and material science which are utilized to analyze nuclear forensic samples. This allows NFAC to provide technical nuclear forensics analysis US government.

Technical Basis

There are two types of physical processes which are exploited for a nuclear weapon: fission and fusion. Nuclear fission is defined as neutrons colliding with atoms which may cause the nucleus to split apart. The breaking of nuclear bonds results in the release of energy, for example approximately 200 MeV[5] per neutron is released from the fissioning of U^{235}. If all the atoms in one gram of U^{235} fissioned there would be 8.2115×10^{10} Joules released[6]. For comparison 1 ton of TNT releases 4.184×10^{9} Joules[7]. This illustrates that breaking of nuclear bonds releases more energy than breaking chemical bonds.

Fusion is the process in which two or more atomic nuclei are fused together to form a single heavier nucleus. Depending on the binding energies of the nuclei determines the amount of energy released from a fusion reaction. The use of hydrogen and tritium in thermo-nuclear weapons produces a yield much larger than a fission device.

An RDD explodes radioactive material in a populated area resulting in the spreading of the radioactive material. Radioactive material is composed of radionuclides which are atoms that undergo spontaneous nuclear transformation by releasing energy. All elements have radioactive isotopes[8] and all atoms with more than 82 protons are radioactive with the exception of Bi^{209}. There are three types of radioactive decay alpha, beta, and gamma. Alpha decay is where an unstable nucleus emits a Helium atom (2 neutrons and 2 protons also called an alpha particle) see Equation 1. Beta decay is where a nucleus simultaneously emits an electron and an antineutrino see Equation 2.

Equation 1 Example of Alpha decay, radium decays into radon releasing a helium atom and releasing 94.45% of the time 4.784 MeV and 5.55% of the time 4.601 MeV.

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[5] MeV is an abbreviation for Mega-electron Volt or 1 Million electron volts. An electron volt is defined as the kinetic energy of an electron as it falls through a 1 volt potential. $1 \text{ eV} = 1.60219 \times 10^{-19}$ Joules

[6] This is a calculated value with the assumptions of pure U^{235} and complete fission of all U^{235} atoms. An idealized situation used to illustrate the difference in energy between breaking chemical and nuclear bonds.

[7] The amount of energy released from TNT is a defined value and not directly measured as agreed to by treaties. See NIST Guide to the SI entry for TNT http://physics.nist.gov/Pubs/SP811/appenB8.html

[8] Isotope is an atoms that have the same number of protons but a different number of neutrons. It is important to note that isotopes cannot be separated chemically. Examples of isotopes: Uranium 235 and Uranium 238, both have 92 protons, but U^{235} has 143 neutrons while U^{238} has 146 neutrons.

Equation 2 Example of beta decay, Cobalt 60 decays into Nickel 60 with a release of 2.820 MeV.

The energy released from a radionuclide, is quantized and discrete, with each radionuclide releasing an alpha, beta, or gamma particle at a different energy than other radionuclides. For example, 94.45 percent of decays from radium emit a 4.784 MeV alpha particle and 5.55 percent of decays emit a 4.601 MeV. While Uranium 235 four most likely decay schemes are 55 percent at 4.3978 MeV, 17 percent at 4.3661 MeV, 5.7 percent at 4.2147 MeV, and 5.0 percent at 4.5964 MeV. These decay schemes give a unique decay spectrum to every radionuclide.

Exploiting the physical characteristics of the elements, i.e. mass, decay spectrum etc. a determination of the composition of material can be made. These characteristics can yield information about what processe(s) may have produced the material. Each isotope that undergoes fission has a probability in breaking into different isotopes. This is referred to as fission yields and varies by isotope and by what neutron spectrum it was exposed to. Figure 1 plots the fission yields for ^{235}U from thermal and fast spectrum (14 MeV). Note how the fast spectrum has higher probability of having fission products between the two peaks and the thermal higher probability of producing fission products in the peaks. Fast and thermal gives extremes to highlight how a changing fission spectrum will change the relative quantities the fission products. Different reactors and other processes have different neutron spectrums, by analyzing what the fission products along with relate actinides a will help determine which reactor or process the material produced the material.

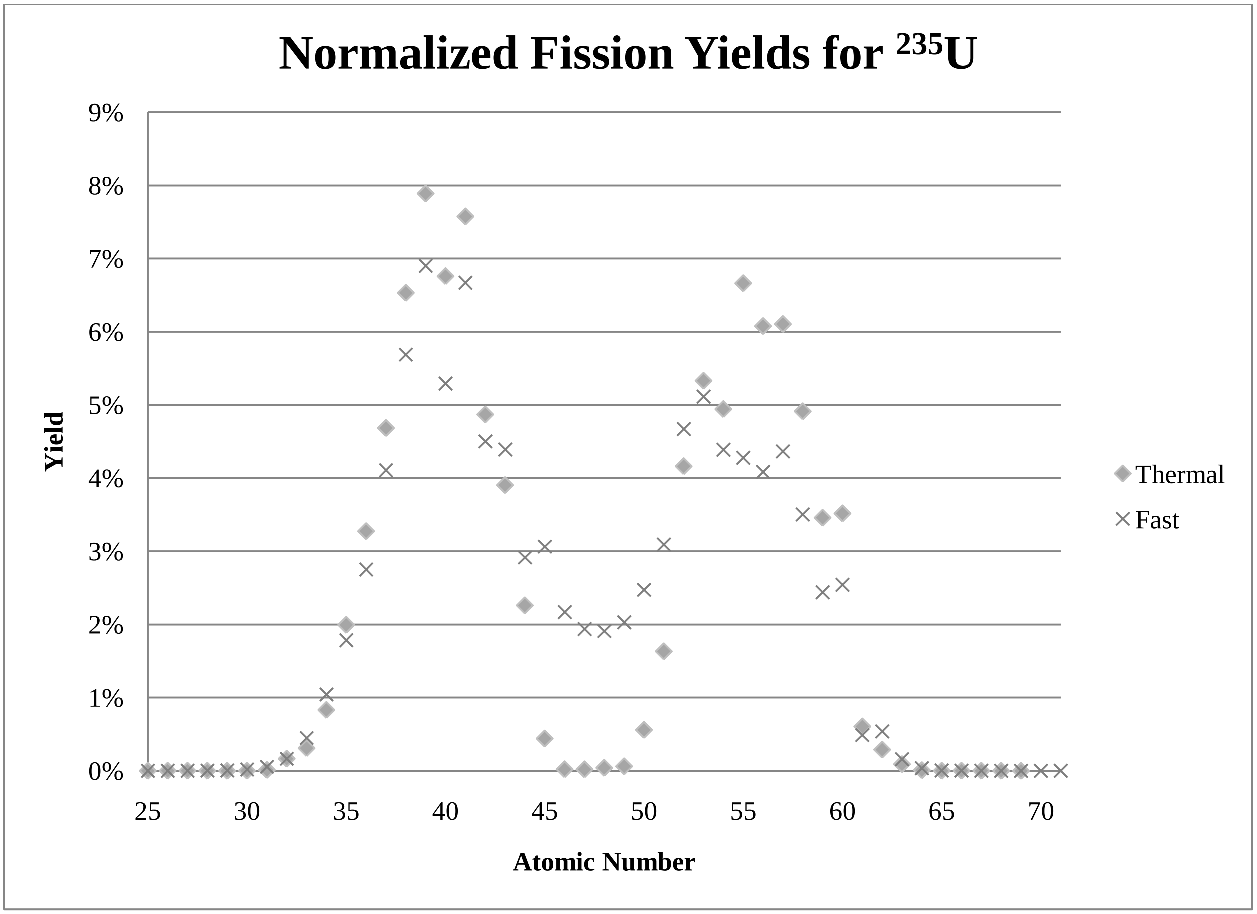

Figure 1 Plot of the normalized fission yields for ^{235}U for fast and thermal spectrum. Note the double peak, isotopes with atomic numbers between 35 to 45 and 50 to 60 are more probable, especially with fission from thermal neutrons.[9]

Material Handling and Analysis

Nuclear materials must be handled carefully and with appropriate protection based on what health risks are posed. NFAC has several capabilities to handle nuclear materials over a large range of activities. First, radioactive materials with a very high dose rate, for example spent fuel must start out in shielded cells. These contained enclosures have thick shields to protect the operators from receiving a dose of radiation. The material is handled with "manipulators", which are mechanical arms with a simple grasping appendage. Manipulators allow the material to be moved, samples to be taken etc… without risk of exposing the operator. The shielded cells are kept under a slight vacuum to ensure any leak will pull air from the outside in and be filtered before being released to the environment. Material that is radioactive, but can be contained by thinner shields and hands and arms can be protected by thick gloves is placed in a glove box. These shielded boxes are kept under a slight vacuum and allow the technician to put his or her

[9] The fission yield data was obtained from Lawrence Berkeley National Laboratory (LBL) and can be found at http://ie.lbl.gov/fission.html. Thermal and Fast data was from T.R. England and B.F. Rider, Los Alamos National Laboratory, LA-UR-94-3106; ENDF-349 (1993).

hands inside long thick gloves in the box to manipulate material. Next, you have radiological hoods which are similar to chemistry fume hoods except they are able to contain small amounts of radioactivity. Then there are environmental labs, which can tolerate only very small amounts of radiation. Then there are the clean laboratories were materials must have almost no radioactivity. Within the clean laboratories is a gamma counter that is 50 feet underground built out of steel taken from a battleship built before the first nuclear weapons test. This allows for very accurate gamma counting, as background radiation has been shielded close to zero.

NFAC has several analytical machines at its disposal for identifying atomic composition of a material sample. One is a thermal ionization mass spectrometer (TIMS) is has the best sensitivity and is operated in the clean labs. Another instrument is an inductively coupled plasma mass spectrometers (ICP-MS) of which there are two in the clean labs and one in the radiation laboratories. There is an inductively coupled plasma emission spectrometer (ICP-ES) located in the radiation laboratories. The underground counting facility has four ultra sensitive gamma spectrometers. There are several alpha spectrometers along with liquid scintillation spectrometers for detecting beta particles.

NFAC is able to detect Pu down to a femtogram (10^{-15}g) in solution. Full uranium isotopics can be obtained with approximately one nanogram (10^{-9}g) of material. NFAC is able to detect Cs-137 to one picoCi (10^{-12} Ci) of activity. These capabilities allow NFAC to determine what isotopes are in a given sample of material. These measurement techniques meet or exceed ISO 17025.

Nuclear Forensics

There are two main questions that nuclear forensics attempts to answer. First, what type of material is it and what threat does that material pose to the US. Specifically is the material special nuclear material (SNM)[10] or radioactive material with potential use in an RDD. Material for an RDD just has to be a radionuclide. However, there are many legitimate reasons for having radionuclides, for example many medical tests and cancer treatment's use radionuclides. Both radionuclides and SNM are controlled by the US government.

The second question is where did the material come from? What nuclear reactor was it produced in, when was it produced has it been reprocessed; was it made in the U.S. or in a foreign country. Any clues about where and when control of the material was loss. It is important to note that who made the material made not be the same as who lost control of the material. If possible, the answer to both those questions is desired. This is why traditional forensics is combined with nuclear forensics work to improve the accuracy of the answer. The FBI operates the

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[10] SNM is defined by Title I of the Atomic Energy Act of 1954 as plutonium, 233U or uranium enriched in the isotopes ^{233}U or ^{235}U.

Radiological Evidence Examination Facility (REEF) at SRNL. REEF was established to handle radiological evidence and is able to perform traditional forensics on the evidence. This setup allows integration of traditional and nuclear forensics at one location.

Figure 2 illustrates how interdicted material might be processed. Note that the traditional forensics work is performed separate from the tests performed by NFAC. The traditional forensics feeds into the predictive models and the into the decision making on attribution. Traditional forensics is able to help with the predictive models if it is able to provide information that limits the possible reactors to be analyzed.

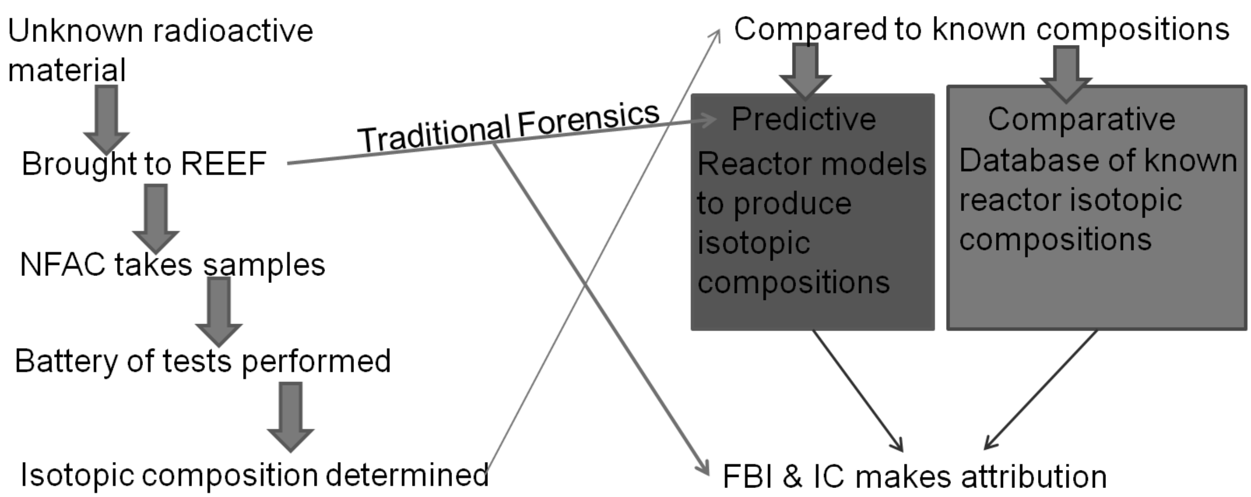

Figure 2 Example of interdicted material might be processed. REEF is an acronym for Radiological Evidence Examination Facility, which is an FBI lab and is located at SRNL. Traditional forensics is performed at REEF on radiological material. That information is used to improve the predictive models and also feeds directly into attribution.

Note that measured data must be compared to known compositions from a database. This database of isotopics has two components. First, is the directly measured isotopics the second are isotopics from reactor physics models. Currently research is underway at SRNL to expand the isotopic database and to improve reactor physics models for nuclear forensics work. An example of this research is a project to sample domestic spent research reactor fuel at SRS. Once samples of the spent fuel are taken, they are treated as if it were an actual case and all regulations required for handling material that may be used in a court of law are followed. At the same time the research reactor is modeled using a variety of nuclear physics codes and with different amounts of detail in the model. This gives the ability to find out what parameters are important in the construction of models that give accurate answers. The exercise has four functions, first is to give the NFAC team practice, second is to uncover any problem or potential problems with the NFAC procedures, third is to add the isotopic composition of another research reactor to a database, and fourth is to determine how much detail and what code or codes work best to model research reactors for the purpose determining isotopic composition. Figure 3 is a flow chart that illustrates the steps taken to investigate how much detail about a research reactor is needed to enable a model to give accurate isotopic composition.

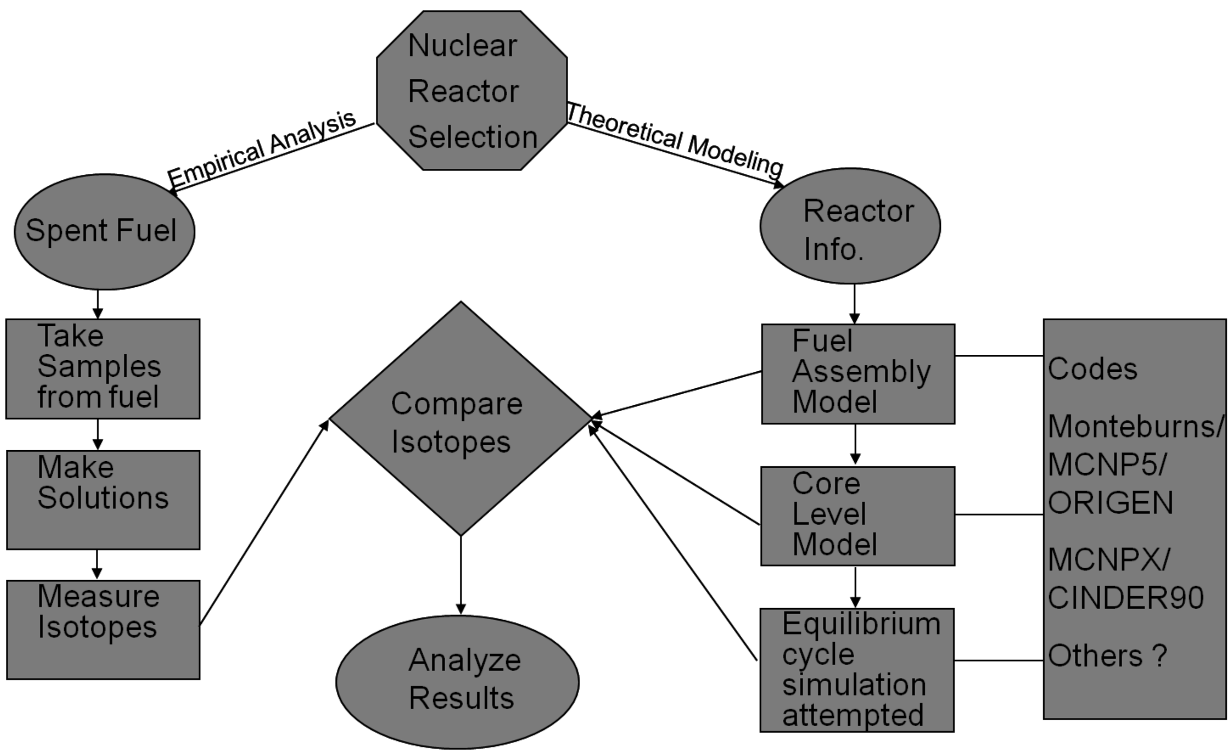

Figure 3 Flow chart of how research is being conducted to determine what information is important in a reactor model to obtain accurate isotopic composition information.

Currently nuclear forensics faces several limitations. First, is a larger more expansive isotopic database would improve the accuracy of attribution. Efforts are underway to improve existing databases, but many countries or companies do not want to allow their spent fuel to be added to such a database. Another limitation is scientists, engineers, and technicians involved in doing nuclear forensics are not able to work on it full time. All of them have other responsibilities and projects; therefore care must be taken to maintain their expertise in areas needed in a nuclear forensics analysis. Another potential limitation is the aging work force. Nuclear forensics has a problem that most of the practitioners are retiring or near to retirement. Radio-chemistry programs at US universities have diminished over the past decades with the remaining universities focused on radio-pharmaceuticals. None of these limitations are insurmountable, but actions need to be taken to ensure the US does not loose its nuclear forensics capabilities.

Conclusion

NFAC analyzes radioactive material to help with the attribution of the material. NFAC is tasked with maintaining capabilities in the areas of nuclear forensics, improve methods through research, and train the next generation of scientists, engineers, and technicians in the art and science of nuclear forensics. NFAC is integrated with the NTNFC and is an integral part of the nuclear forensics capabilities of the US. Nuclear forensics techniques are based on identifying the isotopes in material and determining what possible physical conditions could have created such a material. SRNL conducts research to improve methods in the area of nuclear forensics and the research gives the opportunity to test NFAC procedures.