Detectors based on active neutron and x-ray interrogation can confirm the presence of bulk explosive threats such as landmines, improvised explosive devices, and unexploded artillery shells buried in soil.

Buried bulk explosive threats are a major concern to the armed forces and public security agencies of many countries. Nuclear methods to detect these threats have been studied extensively since the 1950s. Research in this area has concentrated on neutrons and photons as probing and emitted particles because of their deep penetration. Some reactions involving these particles and the buried materials can be used to identify explosive substances, making them good candidates for confirmation sensors: slower devices that confirm the presence of an explosive following initial detection by less-specific, fast-scanning sensors.

Nuclear reactions that generate characteristic radiation capable of identifying an isotope generally have relatively low cross sections (low probability of the reaction happening). To provide results within practical interrogation times, techniques using such reactions require intense sources and consequently large amounts of radiation shielding for personnel and detectors. Though personnel shielding can be significantly reduced by remote operation, this generally relegates active interrogation methods with characteristic radiation emission to either fixed-position roles, such as portals, or vehicle-mounted applications.

Our research, with Bubble Technology Industries (BTI, Chalk River, Canada), has led to the development of a thermal neutron analysis (TNA) sensor as part of a tele-operated vehicle-mounted multi-sensor large-landmine detector. The technique confirms the presence of nitrocellulose explosives by measuring characteristic capture gamma rays following absorption of thermal neutrons. Four multi-sensor systems with TNA were put into service with the Canadian Forces in Afghanistan in 2002, making them the first militarily fielded TNA sensors and confirmation sensors for landmines.

We are developing an advanced next-generation TNA using an electronic neutron generator in place of the present isotopic source, faster higher resolution scintillators, improved geometrical design, and analysis software. We completed extensive tests in realistic conditions in Spring 2011 (see Figure 1) and we are currently analyzing the data.

TNA cannot reliably detect homemade explosives that have no nitrogen. Probing with fast neutrons (a technique called fast-neutron analysis or FNA) can excite gamma rays from carbon and oxygen found in excess in these explosives. To enhance the signal from the target and suppress background noise, we are using a generator that produces back-to-back neutrons and $\alpha$ particles (a technique called associated-particle imaging) to identify the volume in which the neutron produces a gamma ray by tagging its time of emission and direction (see Figure 2).

An alternative to the above neutron-in, gamma ray-out reactions is photoneutron production. A gamma ray of high enough energy can cause a particular atomic nucleus to emit a neutron. The emitted neutron spectrum from an isotope is discrete
if monoenergetic photons are used. We have available high-resolution spectrometers that can measure the neutron spectra, and hence identify the isotope. This method, called monoenergetic gamma ray photoneutron spectroscopy, may have simpler spectra than TNA and FNA, as well as low inherent natural neutron background. Others have developed prototype compact gamma sources, and we have conducted modeling studies that demonstrate the feasibility of using this method to detect explosives.

Nuclear reactions intended for detectors carried by people or small robots need significantly larger cross sections than those intended for vehicle-mounted or fixed-point applications. This generally rules out characteristic radiations, but identification can still be achieved by imaging. For buried target applications, only backscatter imaging can be considered. Our research on person-portable systems has focused on neutron and x-ray coded-aperture backscatter imaging.

Neutron backscatter detection involves irradiating the ground with fast neutrons and detecting the thermalized neutrons that return. Hydrogen, abundant in explosives, is preferentially detected. A Defence Research and Development Canada Suffield/BTI prototype neutron backscatter imager employs a 40 cm × 40 cm thermal neutron sensitive scintillating screen and an array of crossed wavelength shifting fibers to map neutron interactions in two dimensions (see Figure 3). A 200 g wax target buried 1 cm in sand can be imaged in 5 minutes with a fission source.

In x-ray coded-aperture imaging a precisely designed binary mask is placed between the photon source and a large-area position-sensitive planar detector. Since the mask design is known, the photon source distribution can be reconstructed by convolving the detector response with the shadow pattern cast by the mask. Figure 4 shows an early version of an x-ray coded-aperture imager jointly developed by us and by the University of California San Diego (left). On the right is a 90-minute exposure of a landmine, filled with 70 g of a TNT x-ray simulant and buried under 1 cm of loose dirt, using a low energy gamma-ray source.

The various nuclear detection methods we have presented here are proving successful at addressing the major problems plaguing explosives detectors. The confirmation detectors help deal with the high numbers of false-positive detections while the electronic neutron generator addresses the requirement for heavy shielding. Additionally, fast neutron analysis detects alternate explosives, photoneutron spectroscopy may avoid the problems with the background from naturally occurring gamma ray sources, and backscatter imagers show real promise for translating the accuracy of neutron detectors into the convenience of a
person-portable device. Finally, the portable x-ray imager may provide users with an actual real-time image of the buried explosive.

Our future work involves getting the TNA sensor to production level and making extensive improvements to prototypes (in hardware and software for the backscatter imagers). We will also conduct preliminary experiments following modeling studies on photoneutron spectroscopy, make improvements to increase image acquisition speeds, and develop algorithms designed to more accurately identify materials based on information provided by the x-ray backscatter imager.

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John McFee joined DRDC in 1977 and was head of the Explosives Detection Group from 1983 to 2010. He has conducted nuclear physics research for over 40 years, and research on the detection of unexploded ordnance, mines, minefields and improvised explosive devices using a wide range of technologies for the past 34 years.

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