
NEUTRON TECHNOLOGIES (PAPER II)

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EXECUTIVE SUMMARY

Neutrons pass relatively easily through matter and have been used successfully to interrogate the earth for bulk presence of elements, most notably those indicating petroleum. Applying these technologies to explosive detection is challenging because the “bulk” one is looking for can be as small as 100 g or less. The signals from 100 g of material are dwarfed by the background from the rest of the nearby earth and even by cosmic rays. To date, performance at confirming the presence of small amounts of ordnance is poor, even with dwells as long as 10 minutes over areas smaller than a half square meter. This is in part because of variations in the background signal over short distances on the earth’s surface, which can either mask or mimic the ordnance signal.

There is no prospect that current approaches can deliver performance sufficient to be of use in humanitarian demining. There is some prospect that an approach based on high-resolution Ge detectors could resolve the gamma-ray signals sufficiently well enough to allow discrimination of the explosive and background signals. To pursue this requires an instrumentation-oriented research program, looking initially at a combination of phenomenology and engineering development. Using cryogenic Ge detectors, possibly augmented with Compton suppression techniques and cosmic-ray vetoing, a

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high-resolution spectrum could probably be produced that would allow for discrimination into constituent elements. A fairly small number of institutions could pull this off.

We regard such a research program as a high-risk undertaking for humanitarian demining application. A system could probably be produced that would yield a spectrum highly enough resolved to allow for discrimination. However, to develop a version of such a system that would even match current performance, much less speed it up by a factor of 10, would require an enormously expensive system, which would probably require great technical sophistication to operate. A disciplined investigation in this area is more likely to yield either systems or insights of value to the unexploded ordnance (UXO) community, where much larger ordnance items are often of interest.

GENERAL DISCUSSION

Neutrons pass relatively easily through matter but do interact with atomic nuclei. These interactions produce a set of resulting gamma rays (and sometimes of charged particles as well) that can provide a distinctive signature of the nucleus and hence of the chemical element with which they are interacting. Applications of this interrogation technique have been made with both thermal neutrons from radioactive sources and energetic and thermal neutrons from neutron generators.

Because neutrons have a long mean free path in matter, these techniques are best suited to bulk interrogation, "bulk" meaning on the scale of a ton. The most common and most successful application is in oil exploration, where underground neutron generators and gamma detectors have been used for years to confirm the presence of significant oil deposits in the earth's crust. The primary signature is the presence of relatively large amounts of carbon.

The analogous signature for explosive detection is relatively high amounts of nitrogen. However, to be useful in humanitarian demining, any of the chemical-specific techniques must exhibit high performance against essentially any explosive in quantities of 100 g. In other words, instead of looking for changes in composition of the soil of several percent, one is looking for changes at the level of 100 ppm.

The small quantities involved lead directly to the challenges for this technology in humanitarian demining. First, the signal received is overwhelmingly from the earth's crust, secondarily from cosmic rays, and only slightly from the target of interest. Thus, the signal of interest must be distinguished from counting fluctuations in the earth and cosmic-ray background, and true spatial variation in the signal from the earth, and temporal variation in the signal from the sky. In other words, the interference comes in two types. First, from fluctuations, which can be noise-like and therefore are, in principle, reducible relative to the signal of interest by counting for long times. (See quantitative discussion #1 in the next section.) Second are variations in the earth's crust that lead to signals that can either mimic or mask the signal of the ordnance. These are a real effect on the ground and cannot be eliminated by counting for longer times. With the relatively low-resolution detectors currently in use, there is no prospect that adequate performance can be achieved in confirming or refuting the presence of 100 g of explosive, even given very long counting times. Using high-resolution detectors might allow discrimination at the chemical element level, leading to adequate performance. High resolution would also reduce backgrounds, thereby shortening counting times. (See quantitative discussion #2 in the next section.)

Two types of sources are proposed for this sort of work—radioactive fission or alpha particle sources, which produce low-energy neutrons that are quickly thermalized, and neutron generators that produce high-energy neutrons. If the latter is used, the possibility exists to look for signatures with the beam on from (n,n') and (n,p) reactions, with the beam off from thermal neutron capture (n,γ) , and finally from neutron activation of “long-lived” (greater than 1 second) nuclear states. All these processes suffer from the problem of masking and mimicking discussed above. In general, the situation is much more complex and the backgrounds harder to understand as the energies of the gammas get lower than in the 10.8-MeV case considered below.

The only prospect we envision for separating the targets of interest from small variations in the background would involve a very expensive upgrade in detector technology, from scintillator materials to solid-state devices. This would permit separation of the gamma-ray peaks of different elements, and consequently the background com-

position could in principle be determined for each location, rather than assumed to be equal to that of some nearby location and subtracted.

The downside of using solid-state detectors is cost and complexity. The detectors require cryogenic cooling. In addition, the needed background suppression may require Compton suppression and/or cosmic ray vetoing.

Developing a system that would do all this, and taking data and analyzing it to determine how good the resolution required for the spectrum must be to yield directly the elemental abundances, would be at least a Ph.D.-level thesis undertaking, with possibly several such undertakings. A limited number of universities could support such research. This would still not yield a system but could yield a test bed to provide the information necessary to assess optimal performance and to support design of a system. Scientific or instrumentation questions include: How good must the resolution be to discriminate elements? Is Compton suppression necessary? Is cosmic-ray vetoing necessary? If background variation is controlled, how long would one need to count for a given signal-to-noise ratio (SNR)? Engineering questions include: What sort of source is needed? Are all three processes—fast neutron, thermal neutron and activation—needed? How is the shielding, and radiation safety generally, to be accomplished? This undertaking would last three to five years and would cost at least \$5 million.

Although such a research project is supportable, we believe it to be high risk in the context of achieving dramatic improvement in the speed of humanitarian demining. Even if the sensor and processing can support discrimination of the spectrum in principle, in practice there will remain the necessity to count for long periods of time, unless an enormous investment is made in buying high-resolution detectors. In addition, the system would be of great mechanical, electrical, and computational complexity if it used a neutron generator. If it used a radioactive source, additional complexity would result from the need for careful handling of radioactive materials near explosives. It is difficult to imagine the path required for successful technology transition in the humanitarian demining application. Nevertheless, such a research program might prove of use to the

UXO community, where there is often interest in confirming the presence of much larger amounts of explosive.

QUANTITATIVE EXAMPLES

We present some sample calculations based on thermal neutrons from a Cf^{252} source developed in the mid-1990s. Results would vary for a differently engineered system or for a concept that looked for lower-energy gammas. These examples are nonetheless illustrative of the challenges.

1. Improving Performance of Current Technology by Counting Longer

A simple example involves the use of thermal neutrons to detect N^{14} via the 10.8-MeV capture gamma ray. The primary background is from Si^{29} in the soil, on which neutrons capture to a 10.6-MeV gamma ray. For a particular NaI detector, the total background is about 100 counts per minute, 60 of which are due to Si in the soil, 20 to cosmic rays, and 10 each to energetic neutrons from the Cf fission and pileup. (The pileup is significant because it means that improvements from simply increasing source intensity will be minimal.) One hundred grams of explosive would add about three counts per minute. Considering only counting noise, we have, for time in minutes:

$$S = 3t,$$

$$N = (100t)^{1/2},$$

which implies that a 12-detector system would have a signal to noise of approximately $\text{SNR} = (1.08t)^{1/2}$, and need more than 20 minutes to achieve an SNR of 5.

Unfortunately, even an SNR of 5 does not guarantee good performance because small fluctuations in the amount of Si^{29} , or the depth at which high silicon layers were found, would easily mask (if the silicon was less than expected or deeper) or mimic (the silicon was more than expected or shallower) the explosive.

2. Improving Performance with Higher-Resolution Detectors

Using detectors that resolved the N and Si peaks would eliminate the problem of Si fluctuation and might further reduce the overall background by an order of magnitude. This suggests that a little more than two minutes counting time would be needed to achieve an SNR of 5, assuming the overall system efficiency could be preserved with the smaller, more expensive Ge detectors. The combination of background reduction for shorter counting time and improved discrimination for acceptable performance are necessary—but may not be sufficient—for a useful system.

BIBLIOGRAPHY

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- Porter, L., and D. A. Sparrow, “Assessment of Thermal Neutron Activation Applied to Surface and Near Surface Unexploded Ordnance,” IDA Paper P-3339, 1997. [This provides a discussion of the phenomenology of soil and explosives, especially as it applies to slow neutron propagation. Data from field tests at two locations are analyzed. Models of signature as a function of ordnance size and depth are developed.]