DEVELOPING LOW COST NEUTRON SYSTEMS FOR THE DETECTION OF EXPLOSIVES AND DRUGS

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Abstract

Detection systems for threat materials using neutrons exploit the capabilities of this radiation to reach inaccessible regions in material arrays and convey composition information through subsequent transmission and/or scattering processes. In this research we contrast the performance of expensive DEXA (dual energy x-ray absorption) and NEUGAT (dual beam fast neutron and gamma ray transmission) scanners with a novel low cost system concept that effectively utilises two beams and has useful performance features.

An objective in threat material detection systems is to have sufficient sensitivity to distinguish threat materials from other materials. Potential users of neutron-based commercial threat material detection systems may in some instances be deterred by the high cost and the high technical know-how required in using them. In this ‘high-tech’ age, the potential benefits of basic counting systems using simple filters in detecting threat materials is often overlooked. While demand for sensitive systems that combine all leading edge technologies is inevitable by richer companies/countries, lower cost systems with at least a modest sensitivity is a priority especially if operator experience can assist in limiting any shortcomings. Such lower cost systems may take advantage of ‘near-spent’ lower-activity radioisotope-based neutron sources (e.g. less than 0.2 µg of $^{252}\text{Cf}$) withdrawn from industrial use. Use of transmission geometry can keep count times
short and counting precision high through use of large bulk combinations of basic plastic scintillators that are easy to fabricate and assemble as robust units. Use of PC based discriminators and counting boards (for example) provides reliable and stable electronic performance.

In this work we investigate use of appropriate filters (e.g. lead) placed in front of large plastic scintillators, to mimic composition detection capabilities of the more expensive systems. Polyethylene, acrylic, aluminium, water and sand are used as test materials having a range of hydrogen content and effective atomic number values similar to threat materials.

1. Introduction

The detection of hidden threat materials (explosives and illegal drugs) remains problematic and subject to false positives and the full potential of neutrons as a probe is yet to be realised. There is substantial international investment in the basic equipment; neutron sources, detectors, electronics and computer-based methods such as real time data processing and algorithm development. Systems are shaped to meet specific applications such as threat detections within cargo in containers, in smaller aircraft containers or packages, in mailed objects, or in hidden cavities in vehicles and buildings. A common attribute of threat materials is that they are fundamentally organic in nature and can in principle be distinguished from non-threat materials through their concentration ratios of carbon, nitrogen, oxygen, and hydrogen. Differences in the H concentration in materials can be detected through fast neutron scattering. The research reported here contrasts the performance of higher cost x-ray and neutron-based systems with a novel low cost system that has useful detection capabilities and potentially simpler requirements for its use. Low cost effective systems of bulk hidden threat materials may be seen by some as an oxymoron. But use of higher cost systems may remain out-of-reach for some organisations and even countries especially in times of recession. In this paper we investigate what can be achieved with simple detection concepts, especially using plastic scintillators and lead filters.
We present experimental results for materials covering a range of compositions and contrast detection attributes of three systems. Our new system uses a ‘weak’ $^{252}\text{Cf}$ source (0.25 microgram), basic plastic scintillators and filters and a PC based counting system. We demonstrate detections based on a simple filtering method and contrast the performance with two dual beam systems firstly based on pulse shape discrimination techniques and secondly on x-ray absorption techniques using a dual element detector linear array.

2. Scientific scope of your project under the Co-operative Research Programme

This project is associated with the following three milestones. This report includes progress in relation to each of these topics amounting to reaching these milestones, especially in relation to demonstrating an effective low cost system.

**Milestones**

- develop and use low cost tools and novel portable radiation probes for detecting nearby hidden threat materials

- develop the concept of using comparative count rates in more than one detector to enhance the capability to detect threat materials. Report on two applications one in the field and one in internal installations

- report on how advancement of x-ray scanning systems in industry impacts priorities in neutron instrumentation developments

Determining composition attributes of materials, especially in the levels of hydrogen content, is well established by the simultaneous transmission of fast neutrons and gamma rays $^{5-10}$ (NEUGAT). For example, electronic separation of neutrons and gamma rays can be achieved in the organic scintillation detectors using pulse shape discrimination. These systems have practical uses described in the literature such as fat measurement in meat $^{6,7}$, butterfat measurement in milk $^{5}$, and water measurement in wood chips $^{9}$ and water in coke $^{11}$. In the fat measurement in meat application, fat is distinguished from lean meat
by virtue of their differing hydrogen concentrations per gram ($8.7 \times 10^{22}$ for fat and $6.1 \times 10^{22}$ for lean meat). CSIRO Australia has recently demonstrated, and is in the process of commercialising, a cargo scanner based on this principle.

3. **Discussion of the results obtained under the Co-operative Research Programme**

**(a) DEXA systems**

An important x-ray based system used widely in hospitals (bone density) and airports (luggage) to determine composition attributes of materials is the dual energy or dual beam x-ray scanner (DEXA system). This is a leading-edge technology for the detection of explosives and drugs. Such scanners may cost up to about $US500,000 and are familiar in their use in all places where security and medical scanning is required, to detect hidden materials and identify their likely composition\(^1\)\(^-\)\(^4\). There machines are primarily designed for scanning on conveyor systems or in other situations where mechanical means is used to move the source/detector system relative to the object/person being scanned.

![Fig.1 Eagle FA DEXA scanner used to scan packaged meat, assess its fat content and to detect physical contaminants](image)

The miniature detector array used in this system is composed of two elements, positioned one behind the other, and separated by a copper filter, allowing detection of two beams of effectively of different energy. A detector element is illustrated in fig.2. The incident x-ray beam is divided into the low energy (LE) beam and the high energy (HE) beams by
the detector element. The HE beam is a filtered version of the LE beam, through the filtering action of the LE detector and the copper filter element.

In this report, in order to set priorities for neutron systems, we demonstrate the performance characteristics of a DEXA system in characterising some standard materials, some of which are illustrated in fig.3. Sheets of polyethylene (2 cm thick), acrylic (2 cm thick) and aluminium (0.7 mm thick) are well as water and sand are used as test materials. The water and sand is scanned while in a polyethylene container (illustrated).

In fig.4 is shown results from the scanning of test materials based on the ratio of transmitted LE and HE beams. Essentially materials placed in the scanner beam filter the x-ray beam in a way which is dependant on their composition (effective atomic number)
and this in turn affects the ratio of the transmitted LE/HE intensities (‘transmission’ is measured as a count-rate or typically counts per 100s recorded in the detectors).

Fig. 4 shows composition response changes as a function of test material thickness. An alternative method of representing the sensitivity of a DEXA scanner, widely used in the industry, is shown by the curves in fig. 5, with graphs known as ‘banana curves’. The sensitivity in separating materials of differing effective atomic number reaches a maximum when the summed LE and the HE absorptions is about 0.5-0.6 of total summed absorptions possible. ‘Absorption’ is measured as the lost counts in the detectors compared to ‘air values’ counts.

Fig. 5. ‘Banana’ curves are shown for a DEXA scanner. The peak value of the curve increases with increasing atomic number of the test material. The scales have been normalised to simplify the presentation.
Building a commercial threat detection system based on DEXA system usually requires expensive components and means of handling and deploying heavy equipment. Manoeuvrability and shielding are a problem in field applications. Electronics systems are usually expensive and generally air conditioning is required to maintain performance capabilities. Measurements using x-ray tube sources can be fast (e.g. less than a second), as is appropriate for scanning on a conveyor belt, essential for industrial applications.

(b) **Dual beam Fast Neutron/Gamma ray transmission systems (NEUGAT)**

NEUGAT dual beam systems have also the capability to measure composition changes in the test materials based primarily on differences in hydrogen levels per gm of material. In fig. 6 is shown a NEUGAT system at GNS science originally, used to measure fat in packaged meat and other primary industries\(^5\)\(^-\)\(^10\) materials.

![Fig 6](image)

The NEUGAT system called ‘Phoebe’ based on a \(^{232}\)Cf source and a 6 litre organic liquid scintillation detector. The source is mounted in the top tank filled with water and the detector (see also fig.7) is mounted under the conveyor. Detected neutron and gamma ray events are separated by pulse shape discrimination\(^7\)\(^-\)\(^11\).

![Fig 7](image)

The NEUGAT organic scintillator cell is viewed by two 5” photomultiplier tubes mounted on opposite end windows. The cell measures 26 cm long by 12 cm wide by 18 cm deep. Such a detector can operate at count rates in excess of \(10^6\) per second if required.
In fig. 8 is shown NEUGAT transmission ratio curves equivalent to the DEXA system curves in fig.4.

Fig. 8.
NEUGAT transmission ratio curves show separations between polyethylene, water/acrylic and sand.

In fig. 9 are shown examples of NEUGAT ‘banana’ curves obtained using the same or similar test materials to those scanned with the DEXA system. These can be compared with the DEXA curves data in fig.5. The NEUGAT system is primarily sensitive to changes in hydrogen concentrations per unit mass, rather than changes in the effective atomic number where the DEXA principal sensitivity lies. The ordering of the curves in the figures is therefore swapped around. For the NEUGAT method, the material with the maximum sensitivity is the polyethylene \((8.8 \times 10^{22} \text{ per gm})\), intermediate sensitivity water \((6.7 \times 10^{22} \text{ per gm})\) and with lowest sensitivity is sand \((\sim 0 \text{ per gm})\).

Fig. 9
NEUGAT ‘banana’ curves for the test materials. The scales have been normalised to simplify the presentation of the graph.
Building a commercial threat detection system based on NEUGAT and pulse shape
discrimination is inherently expensive in terms of the equipment components and in
ensuring a stable performance. The pulse shape discrimination electronics is inherently
temperature sensitive and this approach has found limited use under industrial conditions.
The equipment and shielding is bulky and use of large liquid scintillators is problematic
in the field.

(e) A ‘Low Cost’ system for material discriminations based on a single
solid organic scintillator and Pb filter.

DEXA and NEUGAT systems provide composition data by contrasting the intensities of
two beams separated in the detector, each beam being filtered differently by the
composition attributes of the material under test. The detector mechanism involves
contrasting types of filtering or separation processes to create two beams. Algorithms can
be developed based on the two beams to predict compositions of the test materials. Here
an investigation is made of a simpler beam selection method based on use of an organic
scintillator augmented with a removable lead filter that can be placed between the source
and in the front of the detector. Such a system is consistent with being a lower cost
system to measure composition changes. The example discussed here is indicative of a
class of lower cost systems that employ simple beam filters where there is potential to
explore many options. Apart for low cost, some bonuses of using basic counting systems
with simple filters include improved manoeuvrability, portability, robustness and abilities
to be operated and understood by non-specialists. The source used here is 0.2 µg of $^{252}$Cf.
The mixed beam of fast neutrons and gamma rays is counted directly. Measurements
were made here by counting the number of events in 100 seconds with organic scintillator
(here measuring 26 x 12 x 18 cm) used alternatively without a front filter installed and
then with a filter installed, and the data is combined as if provided from two beams. The
lead filter used here is 4.5 mm thick. The combined data treated as from two ‘beams’ are
then processed and presented graphically as described for DEXA and NEUGAT systems.
The transmission ‘ratio’ and ‘banana’ absorption curves yield similar information to those obtained with the more complex systems, but because of the mixed nature of the beam (neutrons and gamma rays) the curves show some characteristic differences that are interesting and easy to interpret. Nevertheless the data shows separations in the responses to the materials based on composition, with similar usefulness to those of the DEXA and NEUGAT methods. Fig. 10 shows the transmission ratio curves and fig 11 the ‘banana’ curve for the basic low cost system. Suffice to record here that the essential requirement for the detection threat materials is obtained using this simple detector system in providing distinctive responses to the test materials in terms of the transmission ‘ratios’ and absorption ‘banana curves’.

**Fig. 10**
Transmission ratio curve for the low cost filter detector

**Fig. 11**
‘Banana’ curves of absorption low cost filter detector.
4. **Summary**

This research has discussed the merits and costs associated with various types of radiation based dual-beam systems to measure compositions of hidden materials with a view to determining whether they might be threat materials such as explosives and drugs. It is demonstrated that a system requiring lower costs using a plastic scintillator and a lead filter has potential value given a limited budget and indeed provides some bonuses such as robustness, portability and electronic stability due to the simplicity of the electronics. It is notable that more expensive systems often lack features such as portability, flexibility and inherent electronic stability that the low cost system exhibits. Measurement times per data point may be extended to minutes rather than seconds using the low cost system but this appears an acceptable constraint in most applications.

**References (GNS-based):**
