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Fast neutron tomography with real-time pulse-shape discrimination in organic scintillation detectors

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ABSTRACT

A fast neutron tomography system based on the use of real-time pulse-shape discrimination in 7 organic liquid scintillation detectors is described. The system has been tested with a californium-252 source of dose rate 163 μSv/h at 1 m and neutron emission rate of 1.5×10^7 per second into 4π and a maximum acquisition time of 2 h, to characterize two $100 \times 100 \times 100$ mm^3 concrete samples. The first of these was a solid sample and the second has a vertical, cylindrical void. The experimental data, supported by simulations with both Monte Carlo methods and MATLAB®, indicate that the presence of the internal cylindrical void, corners and inhomogeneities in the samples can be discerned. The potential for fast neutron assay of this type with the capability to probe hydrogenous features in large low-Z samples is discussed. Neutron tomography of bulk porous samples is achieved that combines effective penetration not possible with thermal neutrons in the absence of beam hardening.

1. Introduction

The interaction properties of neutrons with matter complement those of X-rays due to their lack of electrostatic interaction. Their scattering properties are largely independent of the atomic number of the elements that constitute the scattering medium whilst, conversely, they interact significantly with light (i.e. low-Z) isotopes particularly when thermalized. This is especially relevant for hydrogen (often as a constituent of water) and also for the other widespread elemental constituents of low-Z porous materials such as carbon, nitrogen and oxygen. These elements comprise a wide range of substances in use for structural applications and construction where non-destructive evaluation can be desirable. The application of neutron radiation is of interest as a complementary tool to X-ray computerized tomography (CT) because X-rays highlight high-Z features very effectively (such as the iron and cobalt in reinforcing bars and calcium in the surrounding cementitious matrix) whilst neutrons are effective for low-mass, low-density features such as porosity, hydration and fissures that attract low-mass deposits. Both neutron tomography (NT) and X-ray CT have a role in the non-destructive evaluation of the internal state and integrity of a wide variety of materials in use throughout the world.

The scientific prior art associated with NT over the last 30 years is very extensive. It has been applied to archeological samples [1,2], fossils and geological materials [3–5], as a probe for hydrogen content in turbine blades and metal casings [6,7], as an assay for nuclear energy applications [8–12], to assess water evolution and flow in electrolyte fuel cells [13,14], to assess the fouling of filter systems [15], the investigation of transport processes in biological matter [16,17], the reverse engineering of metal components [18,19], the imaging of two-phase flow [20], the assessment of components used in fusion energy [21,22] and in security applications for the detection and characterization of contraband [23,24].

Neutron tomography systems usually comprise a source of neutrons, a collimator, a means for obtaining a variety of projections of a given sample (usually a rotating platform) and a detector system. Most applications have tended to source neutrons from a reactor [25–27], a spallation source [28,29], linear accelerator [30] or portable neutron generator [31–34]. Of particular relevance to the source used in this research is the use of the isotope californium-252 (^{252}Cf) in combination with plastic scintillators for time-tagged transmission radiography of residues in nuclear plant [35] and for the characterization and 2D imaging of materials [36]. For detectors most studies have used a scintillation screen (i.e. ^{6}Li-doped zinc sulfide or a plastic scintillator) coupled with a light intensification system; activation foils have also been used. Charge-coupled devices (CCDs) were first applied to NT approximately twenty years ago [37] and have been adopted widely due

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to their ease of use and compatibility with computerized data acquisition systems [38–40]. Recently, the use of plastic scintillators coupled to silicon photomultipliers with a portable D-D generator has been reported for NT [41] and a plastic scintillator (EJ-200) array with PMTs has been reported for induced fission radiography of nuclear materials [42].

By contrast, the use of organic scintillation detectors in NT, affording real-time pulse-shape discrimination (PSD) and thus the potential for combined acquisition of both neutron and γ-ray events, has not been explored extensively to date. However, organic scintillators with PSD (both plastics and liquids) have been used in neutron scatter cameras for the location and spectroscopy of isotopic neutron sources [43].

A further important distinction associated with extant methods of NT is the energy of the neutrons used. For the assessment of features in macroscopic samples cold or thermal neutrons have relatively low penetrating power limiting their use to thin samples. Several reports of the use of fast neutrons for radiography and tomography have been made [44–47] which afford greater penetration desirable for bulk samples. However, their use requires different detection modalities with, for example, either organic scintillators or via prior moderation and then detection of the thermalized neutrons.

Relatively little research has been reported on the use of NT for the assessment of construction materials which forms part of the focus of this work and we are not aware of any reports of the use of fast neutrons for this purpose. Whilst NT has been used to investigate fluid transport in porous media [48,49], in the context of its application to concrete described this paper two studies are prominent: Masschaele et al. [50] reported the use of thermal neutrons to study water ingress in small samples of autoclaved concrete and compared this with X-ray CT; Christe et al. [51] reported on the assessment of reinforced concrete in their comparison of thermal neutron tomography with X-ray CT. Of particular note is that they reported the limiting effect that scattering of thermal neutrons due to hydrogen content had on transmission. This resulted in a darkening and an associated lack of contrast towards the core of samples which was not observed in samples with low-water content such as sandstone and limestone. We reported recently [52] on the use of fast neutrons and a single liquid scintillation detector for the purposes of discerning rebar in concrete samples with a 75 MBq ^{252}Cf source. In this case the detector was shifted from position to position in turn and a general assessment of the relative abundance in terms of atomic number across the sample was inferred. There are a number of excellent reviews summarizing both the NT field and the achievements of specific facilities around the world [53–56].

The first objective of the research presented in this paper was to determine whether non-destructive NT could be achieved with PSD in organic liquid fast scintillators. We are not aware that this has been attempted before. Organic liquid scintillation detectors offer several advantages over existing detection methods for NT. For example, in comparison with two-stage light-conversion approaches based on CCDs, the light-to-electrical pulse conversion is confined within each detector unit obviating the need for downstream light-tight housings and mirror arrangements. In comparison with plastic scintillators (with the exception of EJ299) liquid scintillators exhibit PSD by which separate neutron- and γ-ray event streams can be derived. Real-time PSD [57] simplifies event processing across a detector array with both neutron and γ-ray data available at the point of each step of a scan rather than following extensive post-processing.

The second objective of this work was to explore the use of the liquid scintillation/PSD technique for the characterization of concrete to determine whether deep, macroscopic features such as a large void, could be discerned. Such features can be difficult to probe effectively with thermal neutrons. Whilst X-ray CT is recognized as a mature, high-resolution technique for concrete assay, the resolution of deep-seated features associated with hydration, porosity, water ingress along fissures etc. requires a combination of deep penetration and sensitivity to light isotopes that is not afforded by X-rays.

2. System description

The system described in this paper comprises:

- A relatively small isotopic neutron source,
- A collimator,
- A turntable offering vertical, rotational and horizontal displacement,
- Seven liquid detectors (Scionix, Netherlands) containing the EJ309 scintillant plus two in reserve (Eljen Technologies, TX),
- Two 4-channel MFAx4.3 analyzers (Hybrid Instruments Ltd., UK),
- An electronic counter interface,
- A PC running a dedicated acquisition/control graphical user interface (GUI) in LabVIEW® (National Instruments, TX).

A CAD schematic of the complete system is shown in Fig. 1.

2.1. Source

For the purposes of this study a bare californium (^{252}Cf) source was used with a neutron emission rate of 1.5×10^7 per second into 4π, giving an associated neutron dose rate at 1 m of 163 μSv/h and an estimated γ-ray dose rate 8–10 μSv/h (not accounting for scatter). ^{252}Cf has two main decay pathways, one by α emission and one by spontaneous fission, the latter being the pathway of interest in this case as this is the principal source of fast neutrons.

The fact that the main process by which neutrons are emitted from ^{252}Cf is spontaneous fission is not of significance to this research because the coherence of the neutron emission in time has not been exploited. Rather, reliance has been placed on single-neutron counting. However, ^{252}Cf is one of the most widely-available, sealed, isotopic source materials for such measurements. It also has an energy spectrum sympathetic with this application (an average of 2.1 MeV and a most-probable energy of 0.7 MeV) in terms of transmission characteristics of the samples used. Further, the most likely energy of scattered neutrons in the environment

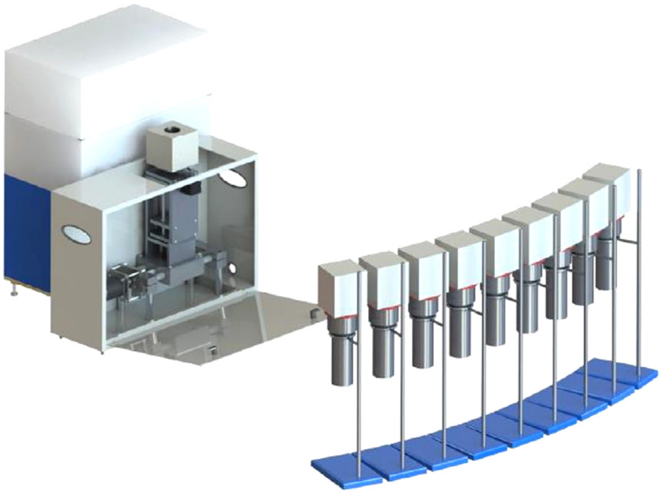

Fig. 1. A CAD representation of the tomography system set-up, showing 9 detectors (right), turntable and sample (center-left) & collimator (left).