TOMOGRAPHY AND ELEMENTAL ANALYSIS USING NEUTRONS IN TRANSMISSION

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Expressions for the calculation of minimum detectable mass and length fractions of elements, compounds and mixtures in a sample using neutron attenuation coefficients are derived, based on previous work done with photon attenuation coefficients. These expression allow quantitative information about elemental concentration to be extracted from neutron transmission measurements and neutron transmission tomography. Calculations are carried out for the detectable mass fraction of hydrogen in a number of sample matrices of industrial interest and of elements in a water matrix highlighting the differences with photon attenuation measurements. Results are presented for three neutron energies, cold (0.001 eV), thermal (0.025 eV) and fast (14 MeV).

The considerable impact that computerised tomography (CT) has had in medicine in the past two decades, both in x-ray transmission and in photon emission modes, has increased awareness of the possibilities that the concepts and applications of tomography have to offer to a wide range of areas with the use of a variety of probes.

There have been significant developments in industrial applications, running almost parallel with the introduction of the techniques into the medical field, particularly in the use of x-ray transmission tomography which provides a valuable tool in non-destructive evaluation of the structure and integrity of materials and components. More recently it has been applied in the field of chemical process engineering to study fluid and particulate flow and to measure changes, e.g. in the formation of bubbles or the variations in density of mixtures during chemical reactions and under different temperature and pressure conditions. A sequence of tomographic images would then also provide dynamic information. However, it must be emphasised that although in transmission measurements it is the distribution of the photon linear attenuation coefficient in a ‘slice’ through the object that is represented, it is possible to make use of Compton (incoherent) scattering and Rayleigh (coherent) scattering photon interactions to obtain additional information about the distribution of the electron density and the atomic number of the materials under examination, in a region of interest. For example, Compton scatter imaging has been demonstrated successfully in the aerospace industry for backscatter analysis of near-surface defects. It has been suggested that the diffraction phenomena arising from mutual interference between coherent scattering of x-rays from various electrons in a spatial region of the order of interatomic separations can be utilised for monitoring bone demineralisation diseases and in the field of security screening to investigate the contents of suitcases for the presence of certain target materials (plastic explosives, narcotics etc).1

Emission tomography, where the distribution of the concentration of a photon emitting radionuclide in a selected plane is obtained, has grown rapidly in the field of nuclear medicine. Coupled with a rotating gamma-camera and referred to as single photon emission tomography (SPET) it has been widely adopted in hospital departments, at relatively low cost. If the photons produced...
on annihilation of a positron and an electron are detected in coincidence around the object containing the positron-emitting radionuclide, an image of the distribution of the concentration of the radionuclide, in a plane can be obtained in positron emission tomography (PET). Because $^{11}$C, $^{13}$N, $^{15}$O and $^{18}$F are pure positron emitters and short-lived isotopes, natural compounds (glucose, water, neuron transmitters etc.) can be labelled and introduced into the body in order to study metabolism and biochemical functions in the human. This is an exciting and active area of research in medicine, providing information for clinical diagnosis. The number of PET systems is increasing worldwide, despite the requirement for a cyclotron to produce the positron emitters and the relatively high costs involved.

A positron emission camera has also been built for industrial applications; in the main it has been used to reveal the distribution of lubricant in operating engines and test rigs, but may also be employed to study flow in fluidised beds, hoppers and paste extruders. The use of $^{68}$Ga (68 min), eluted from a generator carrying the parent nuclide $^{68}$Ge (271 d) and also of $^{22}$Na (2.6y) makes the siting of the camera independent from its proximity to a cyclotron source. Similar areas of industrial interest are being explored using single (and multiple photon) emitting radiotracers to enable gamma-ray emission tomography to be performed. For example, a scanning system has been developed to study the generation of corrosive environments in PWR steam generators using a full-scale simulation of a critical plant component.

**Neutron tomography**

It is but a short step to realise that multiple gamma-ray emission tomography can be carried out on samples following neutron irradiation by detection of the characteristic gamma-rays. This would then provide maps of elemental concentrations in a section through the sample, since it combines neutron activation analysis with reconstructive tomography. We developed the technique, neutron induced gamma-ray emission tomography (NIGET) in delayed mode, for specific applications, e.g. in order to determine the diffusion of As-based solutions through wood for preservation treatment, the distribution of Ca and Na in bone and in salivary gland stones and the diffusion of fission products in real and simulated reactor fuel elements. In these measurements we have generally used one, well-collimated high resolution semiconductor detector to obtain multiple gamma-ray spectra, or in some cases a NaI (Tl) scintillation detector, when only a few major gamma-rays were of interest and there was no interference between these. However, the acquisition of tomographic data in emission mode, using a single collimated detector is time consuming and imposes limitations on the detection limits that can be achieved and the half-lives of the radionuclides about which information is sought. It is clear that the counting time is also a function of the size of the sample to be analysed and the spatial resolution required for the distribution of the elemental concentration. Arrays of high energy resolution detectors are expensive and developments of position sensitive detectors for gamma-ray spectrometry, although promising, may be limited by energy resolution and to a lesser extent spatial resolution.

It is also possible to obtain maps of elemental concentrations in a plane through a sample by detecting neutron capture prompt gamma-rays whilst irradiation proceeds. (This is akin to carrying out x-ray fluorescence tomography using photons.) The technique, termed NIGET-prompt mode, is suitable for determining the concentration of elements with high neutron capture cross-sections, which on neutron irradiation produce stable isotopes, or very short-lived or very long-lived ones. We have developed and used NIGET-prompt mode to examine the distribution of Cd, Al, Pb, Ca and H in tomographic sections of test components for industrial applications. However, in order to obtain