What can you measure with neutron activation analysis?

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Abstract

Neutrons are penetrative. Gamma rays emitted from neutron interaction with atomic nuclei are also highly penetrative. These characteristics distinguish neutron activation analysis from other near surface techniques (MIR, XRF) and allow a large homogenised soil sample volume to be measured remotely from the surface for the top ~50cms of soil. Different elements are suited to different neutron activation techniques, allowing all major elements found in soil, many trace elements and important transient elements (H, C, O, N, S, ..) to be quantified. The ANSTO NASA-C instrument under development utilises a field portable compact pulsed neutron generator for Inelastic Neutron Scattering, Prompt Gamma Neutron Activation Analysis and Delayed Neutron Activation Analysis techniques simultaneously. Testing of the system components with synthetic soil tanks provides data to determine the minimum detection level for Carbon. An operational field instrument is likely to take 1-2 years further instrument development.

Keywords: soil carbon, neutron activation, neutron generator, gamma, spectroscopy, moisture, soil composition.

Introduction

Neutron activation analysis is a useful compositional analysis method that has been effective in industrial niches such as oilfield borehole logging (Ellis 1987, Ellis & Singer, 2008), conveyor belt bulk analysis for the cement industry, radiation laboratory analysis (Nargolwalla & Przybylowicz, 1973) and non-destructive analysis of refractory ores. Various limitations, from the availability of nuclear reactor beam time to occupational health and safety requirements for transport and handling isotopic neutron sources has led to limited analytical use. Modern compact pulsed neutron generators are portable mini accelerators whereby the neutron radiation may be switched off to overcome these limitations to great advantage for non-destructive surface soil analysis.

Neutron activation analysis is a general terminology to describe several different analysis techniques, all based on neutron interactions with an atomic nucleus. The first distinction is the nature of the interaction. The incident neutron may simply scatter off the stationary nucleus depositing energy or slowing down without gamma ray emission. Neutrons may inelastically scatter off the target nucleus depositing energy and cause that nucleus to transition to a temporary excited state releasing energy in the form of a gamma ray characteristic of the target. Neutrons may also be captured by the nuclear interaction resulting in a new isotope and the possible emission of a characteristic gamma ray. The gamma ray emission from a neutron capture reaction may be either prompt (~immediate) or delayed (half life of activation isotope).

Another distinction is the energy of the incident neutron. Fast neutrons (>1 MeV) are required to activate certain elements for an inelastic scattering reaction. These fast neutrons must have energy greater than a threshold for an Inelastic Neutron Scattering (INS) reaction to occur. For example Carbon measurement by INS requires the incident neutron energy to be greater than

4.5 MeV. Fast neutrons are not captured until they scatter off nuclei, deposit energy and slow down to become epithermal (1-10keV) and thermal neutrons (~0.025 eV or 2.2 km/s). Once thermalised, neutrons may be captured giving rise to either prompt or delayed gamma emission characteristic of the target nucleus.

In practice there are 3 principal neutron activation techniques able to be used for elemental analysis of soils;

Inelastic Neutron Scattering	**INS**
Prompt Gamma Neutron Activation Analysis	**PGNAA**
Delayed Neutron Activation Analysis	**DNAA or abbreviated to NAA**

Table 1. Typical neutron sources, neutron activation techniques and applications.

Neutron source	Neutron activation technique	Neutron energy MeV	Facility or field	Typical application
Neutron generator DT pulsed	INS	14.1	Field	Oilfield borehole logging (C, O)
Neutron generator DD	PGNAA	2.45	Field	Conveyor bulk analysis & borehole logging
Isotopic ^{252}Cf & ^{241}Am	PGNAA	0.5 - 4.5	Field	Conveyor bulk analysis & borehole logging
Nuclear reactor	DNAA	Thermal	Facility	Non-destructive mineral ores
Nuclear reactor	PGNAA	Thermal	Facility	Archaeological artefacts
Neutron generator DT pulsed	INS PGNAA DNAA	14.1	Field	Soil composition mapping

Conventional Neutron Activation Analysis is offered by many research nuclear reactors around the world including the OPAL reactor operated by ANSTO. NAA relies upon measurement of delayed gamma emissions after the sample has been removed from the thermal (slow) neutron flux. PGNAA also use captured thermal neutrons yielding a wider range of elements (H, Si, Fe, Cl, ++) useful for soil and rock analyses. Small isotopic neutron sources such as ^{252}Cf and ^{241}Am provide a continuous 2 - 4 MeV neutron flux that may be used for PGNAA applied in borehole logging.

Methods and Instrumentation

The concept of a neutron activation (INS) field instrument for soil composition (lunar surface, planetary atmospheres and Earth's crust and mantle) was reported by Schrader & Stinner (1961) and developed into a practical instrument for mapping soil Carbon (INS) by Weilopolski et al. (2008). The basic hardware design consists of a neutron generator, shielding and a spectroscopic gamma detection system (Fig. 1). Neutron emission from a neutron generator is isotropic with less than half of the total neutrons generated entering the soil due to simple geometry. Shielding is located between the neutron generator and the gamma detectors to minimise direct flight neutron impact and gamma radiation from capture reactions in the shielding on the detectors.

The principal advantage of modern sealed tube neutron generators is the abilty to switch off the accelerator stopping neutron generation. During field operation shielding is required around the neutron generator to reduce the radiation dose to an operator. Autonomous operation is favoured to remove humans from the immediate vicinity of the neutron generator when switched on.

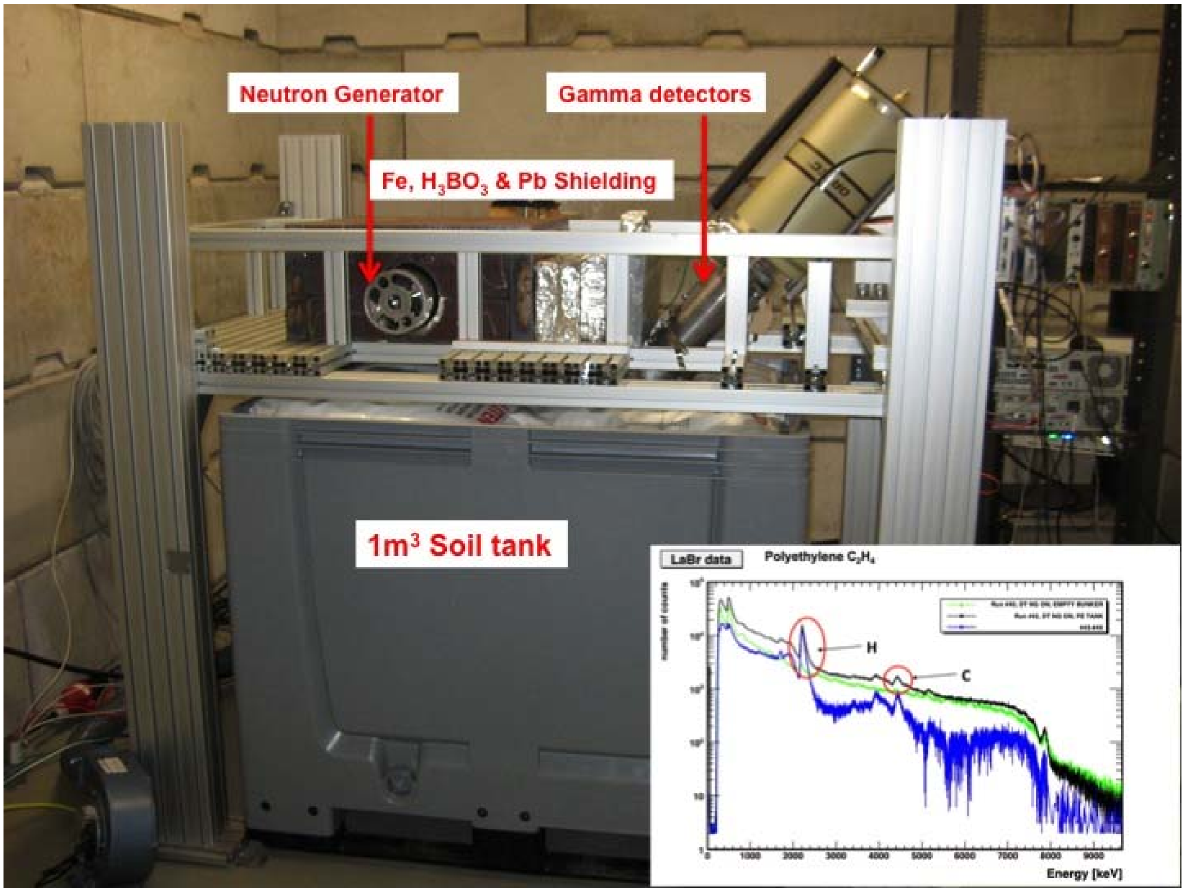

Figure 1. Test apparatus showing the relationship between basic system components for a neutron activation soil analysis instrument. Inset gamma spectra, log counts vs gamma energy 1-10 MeV for polyethylene (C_2H_4) showing C 4.43 MeV and H 2.22 MeV peaks in black, background with tank absent in green and the difference in blue. Neutron generator operated in continuous mode rather than pulsed mode.

Compact neutron generators accelerate Deuterium ions at 50 – 110 keV against a Tritium impregnated target causing a Deuterium-Tritium nuclear fusion reaction providing mono-energetic fast neutrons (14.1 MeV). Neutron generators may be operated in pulsed mode where a short intense neutron burst is followed by no neutron production, then another neutron pulse. Typical operational frequencies are 10 kHz with a 10µs pulse duration. Gamma detectors are synchronised to the neutron generator pulses with tunable time gates to allow collection of gamma spectra coming principally from INS (during pulse), PGNAA (during pulse and ~100s µs afterwards) and DNAA (>>100s µs afterwards). The tuneable pulse regime may be optimised for collection of spectra favouring INS (eg. C, O) PGNAA or DNAA, or configured for simultaneous spectra collected from separate time gates relative to the neutron pulse.

Gamma spectroscopy applied to soil analysis

The guiding factor determining the quality of the analysis is the total number of photons counted and for specific elements the counts above background noise in the specific spectral peak region. There are many obvious contributors to increasing detector counts, from neutron output, interaction distance from neutron generator $1/r^2$, interaction distance from detectors, detector efficiency, spectrum acquisition time and elemental abundance in soil. Another important factor peculiar to neutron activation techniques is the probability of an incident neutron interacting with a nucleus, termed the cross-section, measured in Barns. The nuclear cross-section is specific for each element and is also dependent on the incident neutron energy for fast neutron interactions. Cross-sections vary by 6 orders of magnitude rendering some elements quantifiable at trace concentrations (Cd, Gd, etc.) and some unsuitable to measure.

Conclusions

ANSTO is developing a new and unique nuclear field instrument for measurement of soil composition; particularly carbon. The neutron activation approach has clear technical advantage over existing soil sampling and laboratory analysis for scanning and mapping large heterogeneous areas with variable soil type, climatic region and land use. The very large number of real time analyses provided by the Neutron Activation Soil Analysis technique enables statistically valid measurements of soil C sequestration, land-use inter-comparisons and climate-change related impact on soil composition.

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