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Characterisation of the epithermal neutron irradiation facility at the Portuguese research reactor using MCNP

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HIGHLIGHTS

- An epithermal neutron irradiation facility modelled using MCNPX.
- Foils and TLDs used to measure dose in chamber and compared to simulations.
- Proposed modifications to the irradiation chamber outlined based upon results of simulations.

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ABSTRACT

The radiation field at the epithermal beamline and irradiation chamber installed at the Portuguese Research Reactor (RPI) at the Campus Tecnológico e Nuclear of Instituto Superior Técnico was characterised in the context of Prompt Gamma Neutron Activation Analysis (PGNAA) applications. Radiographic films, activation foils and thermoluminescence dosimeters were used to measure the neutron fluence and photon dose rates in the irradiation chamber. A fixed-source MCNPX model of the beamline and chamber was developed and compared to measurements in the first step towards planning a new irradiation chamber. The high photon background from the reactor results in the saturation of the detector and the current facility configuration yields an intrinsic insensitivity to various elements of interest for PGNAA. These will be addressed in future developments.

1. Introduction

The Portuguese Research Reactor (RPI) is a 1 MW pool-type reactor which has undergone a core conversion to low-enriched uranium, which concluded in 2007 with the assistance of the Reduced Enrichment for Research and Test Reactors (RERTR) programme. Following the core conversion, the radiation fields at various irradiation facilities of RPI have been re-evaluated (Dung et al., 2010; Fernandes et al., 2010; Marques et al., 2011). In this work the evaluation of the epithermal neutron beam of RPI is presented.

The epithermal neutron beamline and irradiation chamber comprise a multi-purpose facility originally designed for Hydrogen determination in materials and for research into Boron Neutron Capture Therapy (BNCT) (Ramalho et al., 2001). Both applications included on-line quantification by Prompt Gamma Neutron Activation Analysis (PGNAA). Depending on the application, the facility can be operated as a thermal or epithermal beam through the interposition of a cadmium filter that absorbs thermal neutrons.

Multi-elemental PGNAA is a sensitive technique for the determination of a range of elements which has been primarily implemented in research reactors using neutron beams extracted through ports. It has found many applications and reached a high degree of sophistication (Anderson and Kasztovsky, 2004). Cold-neutron beam guides and diffracted neutron beams can produce neutrons with energies lower than the thermal range and with a reduced radiation background yielding an increased sensitivity; facilities have been adapted to accommodate large samples for non-destructive assays; epithermal neutrons are used to quantify medium and heavy elements in particular for archaeometry (Blaauw et al., 2005); the detection of x-ray fluorescence rays is used to improve the detection of heavy metals (Jia et al., 2014). More recent developments include imaging (Cippo et al., 2011) and developing alternative facilities, for example employing Am–Be sources for the analysis of aqueous solutions relating to ground

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water pollution (Yongsheng et al., 2015) and D–D generators for the development of mobile PGNNA systems employed in detecting explosives (Bergaoui et al., 2014). The implementation of a PGNAA facility is generally supported by design studies using radiation transport codes to optimise the filters, geometry, acquisition, etc. The deterministic codes are gradually being replaced by Monte Carlo methods, and general-purpose codes have played an important role, namely MCNP which has historically been employed in reactor simulations (Bergaoui et al., 2014; Stella, 2011) and more recently GEANT (Shim et al., 2012). In-house codes have been developed to cover situations unaccounted by the conventional codes, namely neutron interactions within crystal lattices (Mansy et al., 2005).

The initial phase of implementing PGNAA at the RPI will use activation by thermal neutrons, with epithermal PGNAA as a future project with a focus on geological materials.

Preliminary measurements of the background photon spectrum at the current detector port were performed using a high-purity germanium detector (HPGe). The detector became saturated with deadtimes exceeding 90% at any configuration-even with the beam shutter closed. To plan the necessary modifications in order to implement PGNAA, calculations of the radiation field and detector response in various proposed configurations was performed. This work deals with the modelling of the current beam configuration using the Monte Carlo code MCNPX (version 2.5) (Pelowitz, 2008) associated to an existing model of the reactor core (Fernandes et al., 2010) in order to derive the source term.

The accuracy of the beam model will be evaluated by comparison with measurements. The contributions to the radiation background were determined, contributing to the planning of a new irradiation chamber.

2. Materials and methods

2.1. Beam description

Fig. 1 shows the MCNPX model of the beamline and irradiation chamber. The beamline itself contains an aluminium (type 6061) filter that reduces the fast-to-epithermal neutron fluence ratio (Ramalho et al., 2001). The filter, with a thickness of 30 cm, is approximately equidistant from the reactor core and the beam exit, approximately 3 m from the core.

The internal beam collimation comprises a combination of Lead, boral and polyethylene (PE) rings. The external collimator is composed by Pb and a steel beam shutter allowing for two beam sizes, 2 cm and 5 cm in diameter. The irradiation chamber consists of a $(40 \times 40 \times 125)\ \mathrm{cm}^3$ cavity that can be accessed from the top.

The external shield is composed of PE (20–40 cm thickness) followed by a 1 mm Cd sheet and a concrete enclosure. The PE walls contain four fixed structures for the positioning of sample holders centred with the beam shutter. The positions are numbered by increasing order of their distance to the shutter (17 cm, 53 cm, 86 cm and 110 cm). Positions 1 (closer to the core), 3 (current sample position) and 4 (further away from the core) are considered in this work.

A Pb-lined detector port accommodates a HPGe detector (Ortec GMX-2519) at approximately 35 cm from the cavity. The port sits at 65 cm from the shutter, at 30° from the normal to the beam axis. This deflection reduces the maximum energy of the gamma rays from the beam which are Compton-scattered to the detector down to 340 keV, well-below the ^{10}B peak at 478 keV (Verbakel and Stecher-Rasmussen, 2000).

2.2. Chamber measurements

Neutron and photon measurements were performed at positions 1, 3 and 4. At each position, the location of the radiation beam was determined by radiography using Kodak Industrex AA400 films. The films were placed in polymethylmetacrilate (PMMA) frames for irradiation. The frames are centred within the PE walls, and the difference between the centre of the beam and the centre of the PE chamber was determined by reference aluminium wires in the frame. The image of the aluminium wires can be seen in Fig. 2.

For convenience, the full range of neutron energies is divided in four energy groups: 0–0.5 eV (thermal), 0.5 eV–100 keV (epithermal), 100 keV–1 MeV (intermediate) and 1–20 MeV (fast).

Neutron fluence rates were measured using activation foils. Gold foils were used to determine the thermal and epithermal neutron fluence rates by the cadmium-ratio method (International Atomic Energy Agency, 1970). The foils were irradiated both bare and covered with 1 mm-thick Cd. This allows the discrimination between thermal and epithermal neutrons. Cadmium acts as a high-pass filter at approximately 0.5 eV which defines the energy boundary between thermal and epithermal neutrons. The Cd-covered foil is particularly sensitive to neutrons with energies in the order of 5 eV, where an important resonance in the neutron capture reaction in ^{197}Au is located. Pure gold foils were used for increased activity; the corrections for neutron absorption within the sample (self-shielding effect) were included in the derivation of the neutron fluence rates. Foil activities were measured in a standard gamma-spectroscopy system integrating a HPGe detector.

The activation technique for thermal and epithermal neutron measurements is based on the assumption that thermal neutrons have a Maxwellian energy distribution (at the moderator temperature, unless in the vicinity of a strong absorber like Cd or ^{235}U)

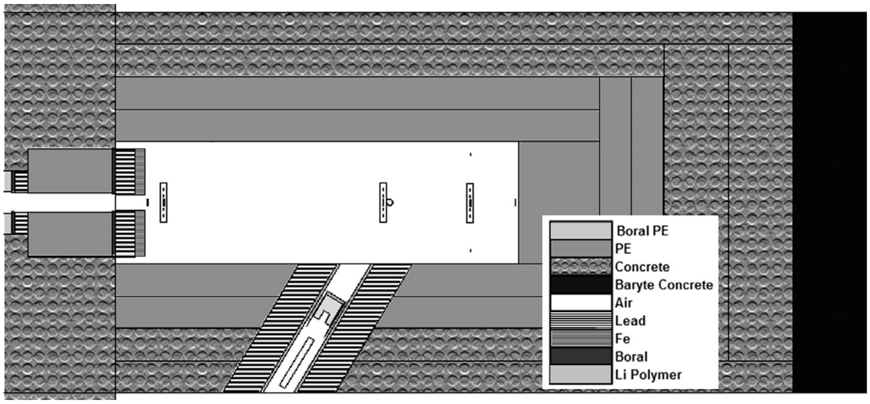

Fig. 1. Schematic view of the current beamline and irradiation chamber, displaying sample positions 1, 3 and 4.