Applied Radiation and Isotopes 135 (2018) 135–141

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Multi-source irradiation facility with improved space configuration for neutron activation analysis: Design optimization

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HIGHLIGHTS

- Neutron irradiation facility consisting of six ^{241}Am-Be neutron sources of 30 Ci total activity is designed and simulated using the MCNP-5 code.
- Neutron sources are arranged symmetrically in a 3D space around a spherical irradiation volume of 65 cm^3.
- The thermal neutron flux is 8.0 × 10^4 n/cm^2 s, which is 98% homogenously distributed over the irradiation volume.

ARTICLE INFO

Keywords:
^{241}Am-Be neutron source
Neutron spectrum
Irradiation facility design
Neutron distribution
MCNP-5

ABSTRACT

A neutron irradiation facility consisting of six ^{241}Am-Be neutron sources of 30 Ci total activity and 6.6 × 10^7 n/s total neutron yield is designed. The sources are embedded in a cubic paraffin wax, which plays a dual role as both moderator and reflector. The sample passage and irradiation channel are represented by a cylindrical path of 5 cm diameter passing through the facility core. The proposed design yields a high degree of space symmetry and thermal neutron homogeneity within 98% of flux distribution throughout the irradiated spherical sample of 5 cm diameter. The obtained thermal neutron flux is 8.0 × 10^4 n/cm^2.s over the sample volume, with thermal-to-fast and thermal-to-epithermal ratios of 1.20 and 3.35, respectively. The design is optimized for maximizing the thermal neutron flux at sample position using the MCNP-5 code. The irradiation facility is supposed to be employed principally for neutron activation analysis.

1. Introduction

Isotopic Neutron Sources (INSs) such as ^{241}Am-Be, ^{226}Ra-Be, and ^{239}Pu-Be have special importance in Neutron Activation Analysis (NAA). The benefits of using INS as irradiator are their very stable neutron flux, small size, and long half-life. Moreover, these isotopes do not require a high-voltage terminal and are inexpensive when compared with the cost of construction and operation of research reactors or neutron generators. Some of the noticeable disadvantages of INS include their relatively low yield and non-Maxwellian shape of the spectrum (Asamoah et al., 2011).

INS flux is obviously smaller than that can be obtained from research reactors by several orders of magnitude. This imposes significant limitations in trace element analysis to a small number of elements with a large enough cross-section. However, INS can be successfully employed in NAA of both minor and major components of bulky samples with large metallic contents, i.e., in order of grams, such as ores, concentrates, and alloys (Myint and Swe, 1994; Jonah et al., 2004; Hibstie et al., 2013). IAEA technical report-465 declared detailed information needed for the determination of silver in lead ores, manganese in living plants and in pyrolusite and ferromanganese, silicon and aluminum in bauxite, tin in cassiterite, cadmium in zinc ore, and boron in steel (Hoste, 1988). Moreover, INS was used for the determination of vanadium content in crude oil down to 1 ppm (Meier et al., 1977; Rizk et al., 1989). Phuong et al. developed a k_0 standardization method for NAA with Am-Be source (Phuong et al., 2012). Others had measured the activation cross-section for 20 elements using such neutron sources (Kaminishi and Nureki, 1983).

Monte Carlo simulations have long been employed in the design of INS irradiation systems. ^{241}Am-B, ^{241}Am-Be and ^{226}Ra-Be INS have fast neutron spectra extended to 6, 11, and 13 MeV, respectively. Irradiation facilities have been designed using graphite, water, polyethylene, or paraffin wax as neutron spectrum modifier by applying one (Idiri et al., 2010; Asamoah et al., 2011; Mensimah et al., 2011; Amgarou et al.,

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https://doi.org/10.1016/j.apradiso.2018.01.032
Received 25 July 2017; Received in revised form 16 January 2018; Accepted 21 January 2018
0969-8043/

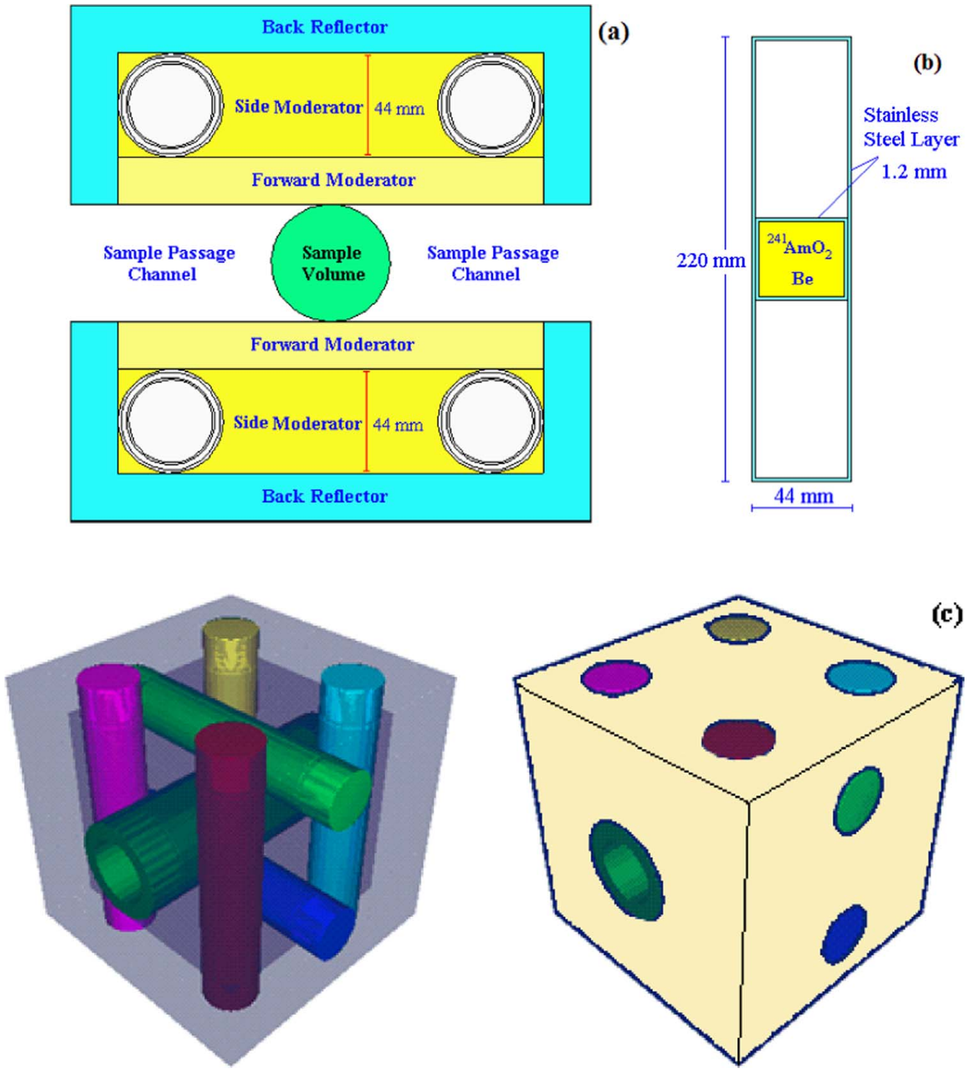

Fig. 1. **(a)** Schematic diagram of irradiation facility model (cross-sectional view along the x-y plane), **(b)** Am-Be source model (cross-sectional view along the z-y plane), **(c)** 3D model of the proposed irradiation facility.

2013; Didi et al., 2015; Bedogni et al., 2016, 2017a, 2017b), two (Shtejer-Diaz et al., 2003), or more (Tuffour-Achampong et al., 2012; Sogbadji et al., 2014) neutron sources. A number of irradiators have been designed with more than one irradiation site (Mensimah et al., 2011; Asamoah et al., 2011; Didi et al., 2015). Some facilities focused on special design features, such as homogeneity (Bedogni et al., 2017a, 2017b) and high thermal neutron fraction from 89% up to 99% (Luszik-Bhadra et al., 2014; Bedogni et al., 2016, 2017a). The design criteria had been chosen to meet the requirements of different applications, such as delayed and prompt gamma NAA (Naqvi et al., 2006; Idiri et al., 2007; Idiri et al., 2010; Nasrabadi and Baghban, 2013; Hadad et al., 2016), detector testing and calibration (Mazrou et al., 2010a, 2010b; Luszik-Bhadra et al., 2014; Bedogni et al., 2016), neutron metrology and dosimetry (Souto and Campos, 2008; Bedogni et al., 2016, 2017a, 2017b), and production of radio-elements with short half-lives (Didi et al., 2017).

The objective of this work is to design a bulk sample irradiation system consisting of six ^{241}Am-Be neutron sources, each having 5 Ci of ^{241}Am activity. The design aimed at the maximization of the thermal neutron flux, possible minimization of the fast-to-thermal ratio, maintaining a maximum possible homogeneity of neutron flux distribution over the sample volume to be irradiated.

In order to achieve these goals, a Monte Carlo simulation technique was employed using the MCNP-5 code, with a special focus on flux symmetry over the sample volume.

2. Materials and methods

2.1. Source specifications

The irradiator consists of six identical ^{241}Am-Be (α, n) sources. They are orphan sources having ^{241}Am activity of 5 Ci or 185 GBq, external diameter of 4.4 cm and length of 22 cm. For our design purpose, the source specifications were speculated from Amersham technical bulletin 1976 and available publications (e.g. Mazrou et al., 2010a, 2010b; Khalil, 2006; Ali et al., 2006).

In this simulation, the ^{241}Am element was considered in the form of ^{241}AmO$_2$ with a total density of 0.482 g/cm^3 and the following composition (wt%): 1.00% oxygen, 15.46% Am, and 83.54% Be (Mazrou et al., 2010a, 2010b and references therein). The geometry of the source considered a cylinder with a double encapsulation of welded stainless-steel. The stainless-steel layer has a thickness of 1.2 mm. The outer dimensions of the capsule are 22 cm length and 4.4 cm diameter. The neutron emission was assumed to be uniformly distributed inside the inner stainless-steel container.

According to Amersham bulletin, the Am-Be source has an emission rate of ~2.2×10^6 n/s/Ci. Thus, the 5-Ci source has a total emission rate of 1.1×10^7 n/s, which is distributed over an energy range extending from 4.14×10^{-7} up to 11 MeV according to the ISO-8529 industry-standard spectrum (ISO-8529, 2001). It reflects all characteristic features of the thick target spectrum of ^{9}Be (α, n) ^{12}C* reaction, which is composed of the superposition of angularly dependent neutron