Nuclear Instruments and Methods in Physics Research A 746 (2014) 74–86

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Experimental and numerical investigations of radiation characteristics of Russian portable/compact pulsed neutron generators: ING-031, ING-07, ING-06 and ING-10-20-120

D. Chernikova [a,*], V.L. Romodanov [b], A.G. Belevitin [b], V.V. Afanas'ev [b], V.K. Sakharov [b], E.P. Bogolubov [c], V.I. Ryzhkov [c], T.O. Khasaev [c], A.A. Sladkov [c], A.A. Bitulev [c]

[a] Chalmers University of Technology, Department of Applied Physics, Nuclear Engineering, Fysikgården 4, SE-412 96 Göteborg, Sweden
[b] National Nuclear Research University/Moscow Engineering-Physics Institute (NIYaU MIFI), Moscow, Russia
[c] Dukhov All-Russia Research Institute of Automatics (VNIIA), Moscow, Russia

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form
28 January 2014
Accepted 29 January 2014
Available online 6 February 2014

Keywords:
Portable neutron generators
Compact neutron generators
Pulsed neutron
Neutron shielding

ABSTRACT

The present paper discusses results of full-scale experimental and numerical investigations of influence of construction materials of portable pulsed neutron generators ING-031, ING-07, ING-06 and ING-10-20-120 (VNIIA, Russia) to their radiation characteristics formed during and after an operation (shutdown period). In particular, it is shown that an original monoenergetic isotropic angular distribution of neutrons emitted by TiT target changes into the significantly anisotropic angular distribution with a broad energy spectrum stretching to the thermal region. Along with the low-energetic neutron part, a significant amount of photons appears during the operation of generators. In the pulse mode of operation of neutron generator, a presence of the construction materials leads to the "tailing" of the original neutron pulse and the appearance of an accompanying photon pulse at ~ 3 ns after the instant neutron pulse. In addition to that, reactions of neutron capture and inelastic scattering lead to the creation of radioactive nuclides, such as ^{58}Co, ^{62}Cu, ^{64}Cu and ^{18}F, which form the so-called activation radiation. Thus, the selection of a portable neutron generator for a particular type of application has to be done considering radiation characteristics of the generator itself. This paper will be of interest to users of neutron generators, providing them with valuable information about limitations of a specific generator and with recommendations for improving the design and performance of the generator as a whole.

1. Introduction

Neutron generators are widely used in different fields of science and engineering as sources of intensive neutron radiation. The latest advances in the field of compact sealed-tube neutron generators towards the development of smaller, lighter, less expensive systems with longer lifetimes and higher neutron yields (e.g. $\sim 10^{11}$ neutron per second) [1] significantly extend an area of their application.

Monoenergetic deuterons, which are interacting with a tritium or deuterium target, allow the generation of fast neutrons with a narrow energy peak and without associated gamma background. Therefore, it is often assumed that a pulsed neutron generator emits neutrons with monoenergies of 2.5 MeV ((D,D)-fusion reaction) or 14.2 MeV ((D,T)-fusion reaction) and in general, it can be considered as an isotropic emitter. This assumption is valid for a stationary neutron generator where target is separated from other constructional elements. However, in the case of a portable/compact pulsed neutron generator, the situation is different, i.e. a target is surrounded by various construction elements/materials which are acting as effective moderators and absorbers of neutrons. This leads to the transformation of the isotropic monoenergetic spectrum of neutrons emitted from the target to the extremely anisotropic angular distribution of neutrons with a broad energy spectrum stretching to the thermal region. At the same time, neutron emission of generator can be accompanied by a high amount of photon radiation which appears as a result of inelastic scattering and capture reactions of neutrons in various materials of generator. Altogether, these phenomena also lead to considerable changes in the time characteristics of neutron pulses emitted by generators.

In addition, during long-term operation elements of neutron generator get activated thus, the so-called activation gamma radiation is formed. The presence of activation gammas can represent a problem for a safe access to the neutron generator during shutdown periods.

* Corresponding author.
E-mail address: dina@nephy.chalmers.se (D. Chernikova).

http://dx.doi.org/10.1016/j.nima.2014.01.061

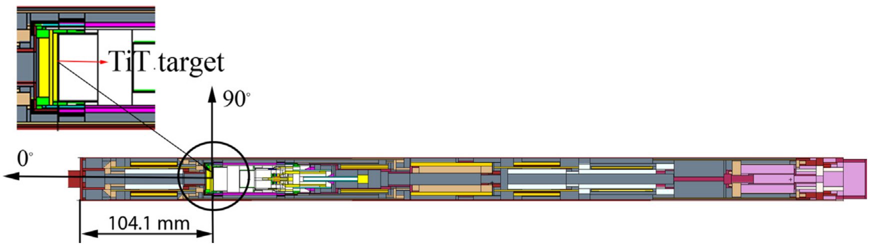

Fig. 1. A visualization of MCNP model for a design of ING-10-20-120 generator.

In the present paper we discuss results of full-scale experimental and numerical investigations of influence of constructional materials of portable pulsed neutron generators ING-031, ING-07, ING-06 and ING-10-20-120 (VNIIA, Russia) to their radiation characteristics formed during and after (shutdown period) operation. This study was initiated by results of earlier investigations discussed in Refs. [2–4].

Numerical and experimental studies were done in a few steps. First, neutron yield of targets was calculated for various energy and angular intervals. These results were used as an input data for follow-up MCNP-4c2 simulations [5]. Then, Monte-Carlo simulations of neutron and photon distributions were performed under the assumption that generator was operating in a continuous mode. For a pulsed mode a real shape of pulses for neutrons and photons was evaluated in two cases, i.e. when the neutron pulse was instant and the pulse had a width[1] (about 0.8 μs for ING-10-20-120, 20 μs for ING-06, 1 μs for ING-031). An investigation of characteristics of activation radiation was performed separately for generator type ING-10-20-120, as an example. In this case the experimental studies were aimed at an identification of reactions and materials which have strongest influence to the value of cumulative activity. Investigations of the neutron generator type ING-07 were limited to experimental studies of time distribution of thermal neutrons emitted in the neutron pulse.

2. Description the simulation process and the simulation set-up

2.1. Configuration of compact pulsed neutron generators types ING-10-20-120, ING-06, ING-031

The design drawings and material composition of generators[2] ING-10-20-120, ING-06 and ING-031 were provided by the manufacturer, i.e. Dukhov All-Russia Research Institute of Automatics (VNIIA) [1]. Thus, an exact geometry for each element of generators was encoded in MCNP4c2 input deck in a way that duplicated the original design. The geometry of input decks visualized for generators ING-10-20-120, ING-06 and ING-031 is shown in Figs. 1–3 with the main parameters of the generators shown in Table 1.

As shown in Table 1 and Figs. 1–3, these three types of generators differ from each other in dimensions, place of TiT-targets, energy of accelerated deuterons and locations of the various construction materials. A center of TiT-target is considered as an origin of coordinates for each generator. Deuterons are accelerated in a perpendicular direction to a plane of the TiT-target in such a way that their direction coincides with a positive direction on the *X*-axis. The ratio of tritium to titanium in targets varies from 1.1 to 2.

[1] A yield of neutrons in the neutron pulse was constant. To a large extent, one can also take into account a time dependence of the yield of neutrons during the neutron pulse.

[2] Drawings included neutron emission units.

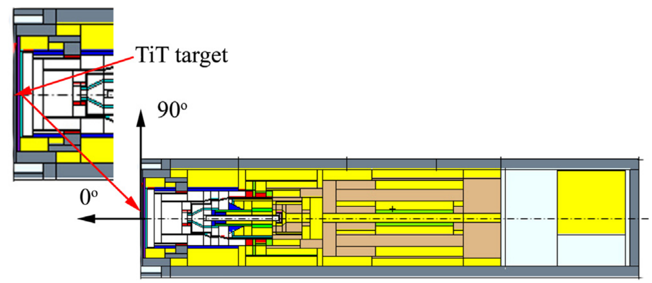

Fig. 2. A visualization of MCNP model for a design of ING-031 generator.

Fig. 3. A visualization of MCNP model for a design of ING-06 generator.

Table 1
Main parameters of neutron generators ING-10-20-120, ING-06 and ING-031.

Type	Length (mm)	Diameter (mm)	Diameter of target (mm)	Energy of deuterons (keV)	T:Ti ratio
ING-10-20-120	607.5	34	8.5	110	1:1.1
ING-06	1126	70	10	85	1:2
ING-031	559	130	62	95	1:2

Construction elements of generators include accelerator units, cooling systems, and isolators. Therefore, their material compositions consist of variety of substances, such as insulating oil, stainless steel, ceramics, glass, polyamide, glass–cloth–base laminate, brass, and ferrite.

2.2. Kinematic calculations of a normalized yield of neutrons emitted by TiT targets of ING-10-20-120, ING-06 and ING-031 tubes

All the generators investigated in the present work use a $T(d,n)^4$He-fusion reaction for neutron production. Deuterons accelerated in the neutron emission unit bombard TiT-target and slow-down in the target material. In this process, deuterium ions with energy up to E_d have a finite probability of undergoing a fusion reaction throughout a region defined by its range in the target material.

The tool kit MCNP-4c2 cannot directly model the deuteron transport and the neutron emission from the $T(d,n)^4He$ fusion reaction for incident deuterons with energies in the keV range. In order to perform such simulations for D–T neutron production one can use SOURCE and SRCDX subroutines (after compilation with the MCNP source code [6]) or calculate relative neutron yield separately [7] and then use it as an input for neutron source in