Radiation Measurements 97 (2017) 35–41

Contents lists available at ScienceDirect

Radiation Measurements

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

The spatial dose rate and energy characterization of a P 385 D-D Neutron Generator using a nested neutron spectrometer and a tissue equivalent proportional counter

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HIGHLIGHTS

- The characterization of a D-D neutron generator is presented.
- Novel nested neutron spectrometer was used.
- Complementary TEPC measurements were conducted.
- The spatial variation of neutron fluence is mapped.

ARTICLE INFO

Article history:
Received 22 August 2016
Received in revised form
12 October 2016
Accepted 19 December 2016
Available online 21 December 2016

Keywords:
Neutrons
Neutron generator
Nested neutron spectrometer
Microdosimetry
Tissue equivalent proportional counter

ABSTRACT

A nested neutron spectrometer (NNS) and a tissue equivalent proportional counter (TEPC) were used to measure the spatial dose equivalent and energy neutron fluence distribution of a P 385 D-D Thermo Fisher Scientific Neutron Generator located in the mixed field dosimetry facility at the University of Ontario Institute of Technology. The P 385 Neutron Generator uses the D-D nuclear reaction to generate neutrons with an expected average energy of 2.5 MeV. The NNS uses a He-3 proportional counter to measure the neutron capture count rate as a function of nested cylindrical moderator thickness. Using the NNS and associated unfolding software, the energy neutron fluence distribution at various locations from the P 385 neutron generator were determined along with other radiation protection quantities of interest. Measurements of the dose equivalent rate were also conducted at the same locations using a 5-inch spherical TEPC and compared to the NNS results. The TEPC was further used to measure the dose equivalent as a function of radial distance from the neutron generator target and also for different P 385 operating conditions.

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1. Introduction

The mixed field dosimetry irradiation facility at the University of Ontario Institute of Technology (UOIT) is equipped with a Cs-137 source (8 Ci, Hopewell Designs, USA), an ISO Narrow Band series X-ray generator (Hopewell Designs, USA) and a P 385 Neutron Generator (Thermo Scientific, USA). The goal of the various radiation sources is to conduct research on detector development for neutron monitoring in mixed radiation field environments. Thus, characterization of the neutron generator is particularly required for the development of neutron monitoring instruments. The P 385 neutron generator is a source of fast neutrons with an average neutron energy of $E_n \approx 2.5\ MeV$ generated by the D-D reaction and a neutron yield of $\sim 3 \times 10^6\ s^{-1}$. The Nested Neutron Spectrometer (NNS) is a recent innovation based on the moderating sphere spectrometer (Bramblett et al., 1960) where spheres are replaced by a set of nested cylinders (Dubeau et al., 2012). The NNS was designed and built by DETEC (Quebec, Canada) and includes the unfolding software required to analyze the measured neutron count-rates and produce an energy fluence-rate spectrum. The P 385 was characterized using the NNS and a 5-inch commercially available spherical tissue equivalent proportional counter (TEPC). In this paper the spatial and energy distribution of the neutron

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http://dx.doi.org/10.1016/j.radmeas.2016.12.008
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fluence for the P 385 Neutron Generator will be presented, along with dose-equivalent rates determined from the NNS and TEPC data.

2. Materials and methods

2.1. The P 385 neutron generator

The D-D nuclear reaction can be described by equation (1):

$$ {}_{1}^{2}H + {}_{1}^{2}H \rightarrow {}_{2}^{3}He + {}_{0}^{1}n \quad Q = +3.26\ MeV \tag{1} $$

The P 385 neutron generator utilizes an ion source and accelerates deuterium ions onto a metal hydride target, containing two deuterium atoms per metal atom, where the reaction presented by equation (1) takes place. For significant neutron production a minimum accelerator high voltage of 40 kV and 20 μA ion beam current must be supplied. The ion beam current can be adjusted up to 70 μA and the accelerator high voltage to 130 kV. For optimum operation and D-D tube life-time, the manufacturer recommends operating with low beam current and high voltage in the upper half range. At 90 kV and 50 μA a neutron output of about $3 \times 10^{6}\ s^{-1}$ is expected with an average neutron energy of 2.5 MeV (Thermo Scientific P 385 Neutron Generator Operation Manual, 2010). The neutron generator was operated with a current of 50 μA and a high voltage of 120 kV for the measurements presented in this paper. A 0.32 cm thick lead shield was designed and constructed to fit over the neutron generator tube to shield the known low energy x-ray component (broad peak centred at 70 keV) emitted by the neutron generator (Wharton et al., 2011). Finally, the P 385 is installed on a sliding track with the ability to adjust the position of the generator in all dimensions with ease.

2.2. The nested neutron spectrometer (NNS)

The NNS contains 7 cylindrical moderators that can be nested into one another. A complete description of the NNS device can be found in (Dubeau et al., 2012). A 2 atm He-3 filled cylindrical (radius = 0.8 cm, height = 5 cm) proportional counter is inserted in the middle of the smallest cylinder and additional cylinders are added one at a time to increase the thickness (volume) of moderator surrounding the He-3 detector, maintaining the detector at the centre. As each cylinder is added, the count rate is measured by the He-3 detector using the necessary pulse-processing electronics and a multi-channel analyzer. In addition, the count rate with the bare detector is also obtained. Thus, one complete set of measurements is composed of 7 count rates obtained with different thickness of moderator and one count rate with the bare He-3 counter. Fig. 1(a) is a schematic diagram of the NNS setup. The axis of the detector and moderators was always aligned perpendicular to the direction of the neutron emission. To generate the neutron spectrum once a set of measurements is obtained the NNS Unfolding Software V 2.8 is applied (Dubeau et al., 2012). Along with the neutron spectrum, the software also provides five neutron dosimentric quantities. These include the neutron fluence rate ($cm^{-2}s^{-1}$), fluence-averaged mean energy (*MeV*), ambient dose-equivalent mean energy (*MeV*), ambient dose equivalent rate ($\mu Sv/h$) and averaged ambient dose equivalent per unit fluence ($pSv\ cm^{2}$). The software contains two unfolding algorithms (the least square algorithm STAY'SL mathematical code and a Maximum Likelihood Expectation Maximization (MLEM) algorithm) and both were used to obtain the optimum results. The STAY'SL algorithm was developed to produce neutron spectra based on activation measurements and the MLEM algorithm is typically used in medical CT image reconstruction (Nested Neutron Spectrometer User Manual, 2015). The two algorithms were used in sequence using the MLEM algorithm first to generate a good guess spectrum which was then used as the guess spectrum in the STAY'SL unfolding algorithm. This two-step unfolding procedure led to acceptable solutions for all NNS measurements conducted. Embedded in the software are a set of count-rate versus neutron energy response functions for each total cylinder combination from the bare detector up to all seven cylinders nested together. An error of 10% has been estimated for the NNS measurements combining the NNS system error recommended from the manufacturer and experimental errors.

2.3. The spherical tissue equivalent proportional counter (TEPC)

The dose equivalent rate of the neutron generator was also measured using a commercially available spherical TEPC (Far West Technology, Inc. CA, USA). The 5-inch TEPC is composed of a tissue-equivalent plastic (A150) spherical shell and a gas cavity filled with tissue equivalent gas (55% C_3H_8, 39.6% CO_2 and 5.4% N_2) at a pressure of 6.65 torr. This gas pressure corresponds to a mass of gas of $(1.630 \pm 0.088) \times 10^{-5}$ kg within the cavity of the TEPC. Under these gas conditions the TEPC simulates a 2 μm diameter unit density tissue equivalent spherical volume. The detector is equipped with an internal alpha source (Cm-244) which provides a lineal energy calibration of 127 keV/μm. Lineal energy is the imparted energy within the gas cavity divided by the mean chord length of the gas cavity (ICRU, 1983). The internal alpha source provides a means of converting the pulse amplitude of the detector output signal to lineal energy. Fig. 1(b) displays the TEPC pulse processing equipment required to conduct the neutron measurements. Using MicroDose 2.2 software (DETEC, Quebec, Canada), the data from two analogue-to-digital converters (ADC 1 and ADC 2, in Fig. 1(b)) was combined and converted into a microdosimetric spectrum. The software combines the two ADC data by looking at the overlap region and adjusting the region to obtain an overlap ratio close to unity. The use of two amplifiers and ADCs with different gains allows for a sufficiently large range of pulse-heights to be measured and capture the full-range of event sizes generated by neutron interactions with the gas cavity of the TEPC. The microdosimetric spectra are represented with lineal energy, y in keV/μm on the horizontal axis consisting of 50 equal logarithmic intervals of lineal energy per decade and with the absorbed dose or dose equivalent rate plotted on the vertical axis (ICRU, 1983). The area under each microdosimetric spectrum is directly proportional to the absorbed dose or dose equivalent rate. Once the measured data was combined and redistributed into logarithmic bins with MicroDose 2.2 the data was transferred to Origin software. Origin was used to calculate the absorbed dose and dose equivalent rates measured by the TEPC and to display the relevant microdosimetric spectra.

2.4. Experimental setup

The neutron generator is housed in the irradiation facility at UOIT. The room is below ground and built with 1 m − thick fortified concrete walls and is licensed by the Canadian Nuclear Safety Commission. A schematic of the experimental setup is shown in Fig. 2. The dimensions of the irradiation facility main room are 7.8 m × 7.6 m with a height of about 4 m. Measurements with both detection methods (NNS and TEPC) were conducted at four different positions around the neutron generator. All positional measurements were conducted with the detectors centred at 100 ± 1 cm from the centre of the neutron generator target and at a height of 127 ± 1 cm. During the NNS measurements a second He-3 detector housed in a 0.002 m^3 solid cylindrical polyethylene moderator was set up in the room to monitor the count rate during all measurements. Additional measurements were conducted with

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