Validating the current-mode of Nested Neutron Spectrometers under high neutron fluence-rates in radiation therapy using a novel passive system with gold foils

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Objective: Nested Neutron Spectrometers™ (NNS, Detect Inc., Gatineau, QC) are Russian-doll model neutron spectrometers that use He-3 counters for thermal neutron detection [1]. These spectrometers are calibrated by the vendor at the Ionizing Radiation Standards Laboratory of the National Research Council of Canada (IRS-NRC) using a reference Am-Be neutron source. During the calibration, akin to the method of Hagiwara et al. 2011 [2], a conversion factor is determined to convert the accumulated charge measured in current-mode operation to the number of neutrons that interacted with the sensitive volume of the He-3 detector. This calibration factor is provided to end-users, typically for determining neutron spectra in particle accelerator and nuclear power plant environments where neutron fluence-rates are high. However, the accuracy of the conversion factor obtained using the Am-Be source (low neutron fluence-rate) is questionable when the neutron fluence-rates are high. A direct validation in a high fluence-rate environment is also impossible as the pulse-mode (an operation mode in which the number of neutron pulses can be measured directly) fails due to pulse pile-up effect under high neutron fluence-rates. Therefore, in this study we sought to indirectly validate the current-mode of the NNS in a high fluence-rate environment using passive gold-foil neutron detectors.

Materials and methods: We developed a novel passive-NNS by replacing the He-3 detector with a gold-foil disc (8 mm radius, 0.1 mm thick and 19.3 g cm^{-3} density) placed between two cylindrical inserts (Figure 1). The gold activation-foil was positioned horizontally at the geometric center of the moderators of the NNS. Unlike the original active-NNS, the passive version does not suffer from pulse pile-up when used under high neutron fluence-rates. Hence, we used both active and passive NNS to determine and compare the neutron spectra generated by the 15 MV beam of a Varian TrueBeam STx linac at the location of measurement (1 m away from the isocenter along the treatment-couch axis at the isocenter height) in a radiotherapy bunker of the McGill University Health Centre (MUHC) as shown in Figure 2.

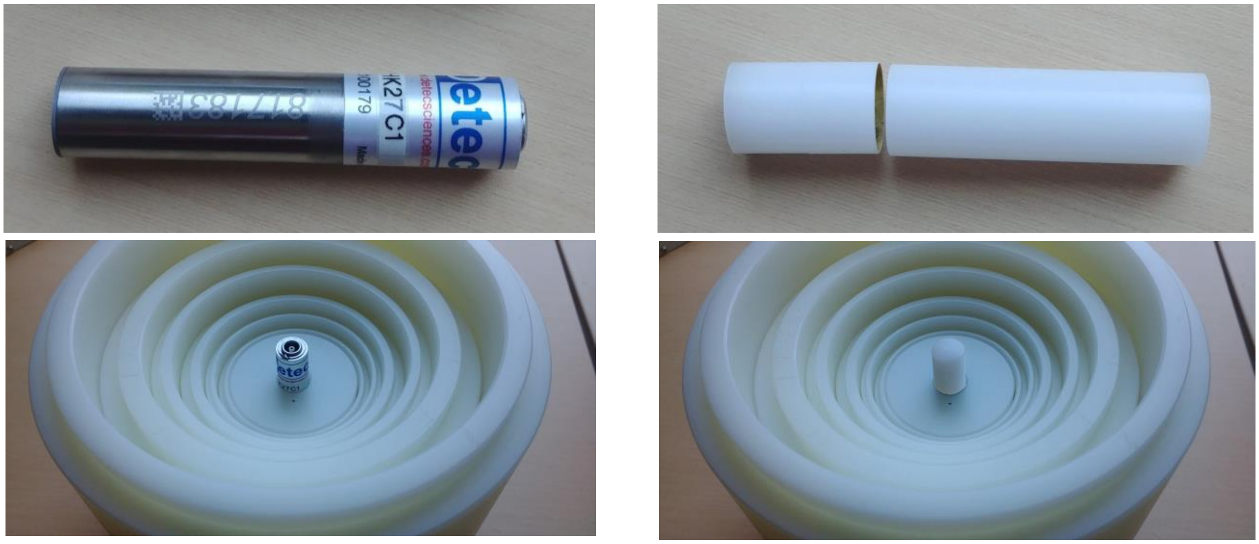

***Figure 1**. The He-3 detector and its positioning inside the nested moderators of the NNS (left). The picture of the two cylindrical insert with the gold foil inbetween and its positioning inside the moderators to have a passive NNS (right).*

The spectral measurement procedure for the active NNS is well established [3]. The electrometer connected to the He-3 detector of the NNS measures the total charge accumulated in the He-3 detector during the irradiation. Using the vendor-provided response functions, calibration factor and an input guess spectrum the raw data are unfolded into a neutron fluence-rate spectrum using the modified MLEM-STOP algorithm [4]. The passive NNS on the other hand, requires more elaborate pre-processing steps to obtain unfoldable raw data. Gold-foils get activated via the neutron capture reaction in a neutron field. The activated gold isotope (Au-198) radiates a characteristic photon of energy 412 keV with a half-life of 2.7 days. With a suitable gamma-ray spectrometer, the characteristic photon can be identified and the saturation activity of the foil can be determined. In our study, we used a High Purity Germanium (HPGe) detector at the SLOWPOKE neutron activation analysis laboratory of Polytechnique Montreal. The response functions of the passive NNS that were needed to unfold the foil saturation activity data—to obtain the neutron fluence-rate spectra—were generated through Monte Carlo simulations of the spectrometer in Geant4 (version 10.4. patch-2). The passive NNS with gold-foils was modelled accurately and its neutron interactions were simulated using the QGSP_BIC_HP physics model in Geant4. The response, defined as the ratio of the number of neutron capture reactions to the neutron fluence, was thus obtained and used to unfold the foil saturation activity data using the modified MLEM-STOP algorithm as for the active NNS.

***Figure 2**. The passive NNS with gold foil in one of its moderator configurations at the location of measurement in the radiotherapy bunker during irradiation.*

Results: The response functions of the passive system with gold foil, as obtained from the Monte Carlo simulations in Geant4 for different moderator shell configurations, are shown in Figure 3.

Figure 4 shows the neutron fluence-rate spectra obtained at the location of measurement during the irradiation of the 15 MV beam in the radiotherapy bunker using both the active and passive NNS. The histograms plotted show the average spectra obtained after three repeated measurements with both the spectrometers and the shaded region is the standard uncertainty of each neutron spectrum. The neutron spectral measurement with the passive NNS had relatively large uncertainties and both the measurements agreed reasonably well within these uncertainties.

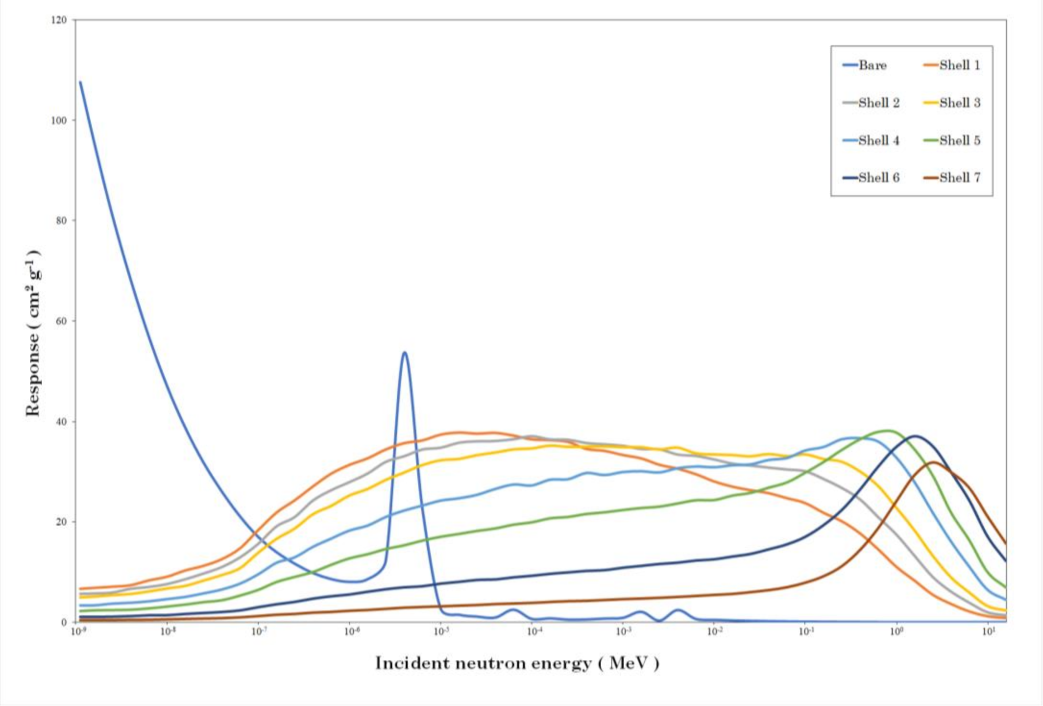

***Figure 3**. The response functions of the passive NNS generated via Monte Carlo modelling in Geant4. Bare represents the model when only the gold-foil with the cylindrical inserts are used and Shell 'X' corresponds to the moderator configuration in which all the moderators up to the 'X'th one are used in the model.*

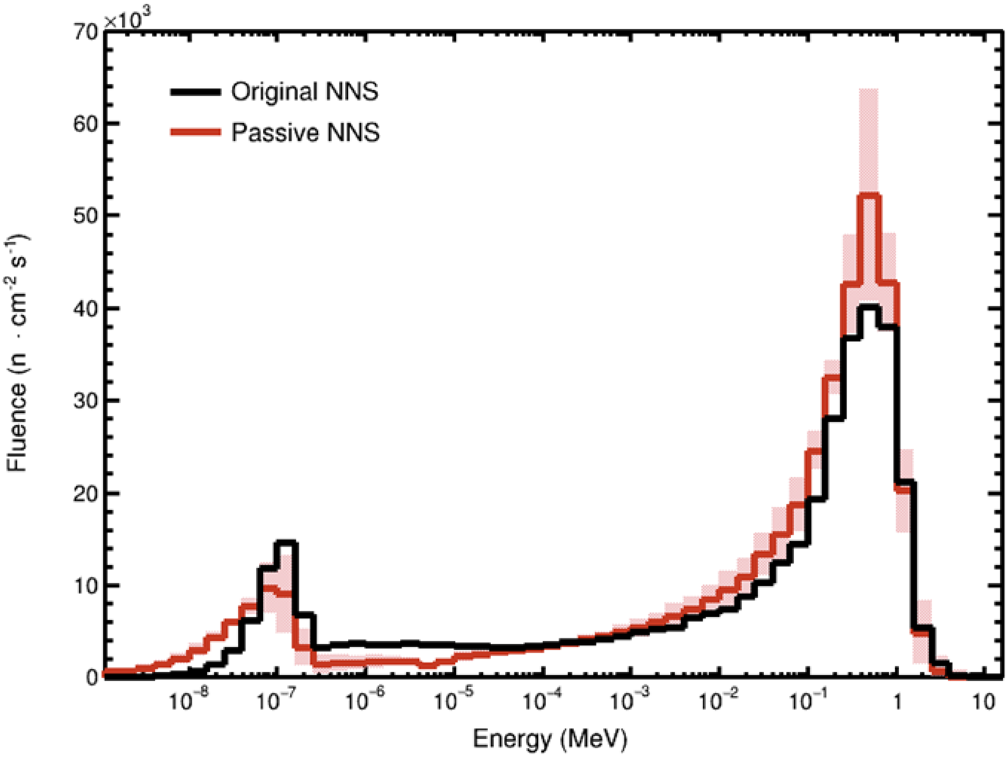

***Figure 4.** The neutron fluence-rate spectra obtained using the Original (active) NNS with He-3 detector and the with the Passive NNS with gold-foils.*

Conclusion: In this study, a passive NNS with gold-foils was successfully developed and a functional workflow to use the spectrometer for neutron spectral measurements was established. The neutrons' fluence-rate spectrum at a location of interest was determined using the active NNS in its current-mode and with the passive gold-foil-NNS and compared. The spectra agreed reasonably well within uncertainties validating the accuracy of the use of the active NNS with He-3 detector in its current-mode under high neutron fluence-rate environments like in radiotherapy.

Relevance to CIRMS: This work was done by the first author as part of his master's thesis. Through the validation of the current-mode of the active NNS, we brought the calibration from the standards lab to the end-user at high neutron fluence-rates. It is now plausible for any user to confidently perform neutron spectral measurements using this spectrometer under high neutron fluence-rates. Hence this research is relevant to the CIRMS mission. The first author, now a PhD candidate, will be continuing the use of this spectrometer to gain more insight into the neutron-induced carcinogenic effects research of his group.

References:

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