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Validation of neutron generator emission rate estimated based on activation measurements during in-vessel calibration of JET neutron detectors

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A robust methodology to enable monitoring of neutron emissions from the fusion devices is needed to allow the determination of key parameters such as fusion power, a range of plasma physics observables, and as input to radiological safety considerations.

A second Deuterium-Tritium Experimental Campaign (DTE2) at JET is planned for 2020 in which up to $1.7\cdot10^{21}$, 14.1 MeV neutrons could be produced. They will be measured by two neutron yield monitoring systems installed at JET: firstly a fission chamber system (KN1) and secondly the activation system (KN2). These systems were absolutely calibrated in 2017 using a characterized ING-17 14 MeV neutron generator (NG) as the calibration neutron source. The neutron emission rate of the NG was measured based on dosimetric foil activation measurements.

An independent analysis of the activation measurements used to determine the neutron emission rate of the NG is presented in this paper. The neutron emission rates of the NG from monitoring activation results were obtained using a detailed MCNP model of the NG and its neutron source properties. In the second case, they were calculated using the FISPACT-II code with neutron flux spectra calculated by MCNP code. Calculated values of neutron emission rate were compared to values estimated based on the activation measurements.

Keywords: activation technique, FISPACT-II, JET D-T campaign, neutron generator emission rate.

1. Introduction

To determine the power produced in a fusion device, an accurate estimation of the neutron yield (Y_n) is necessary. It is a fundamental operational quantity and, being linked to plasma performance parameters, it is an important measure of fusion success. The neutron yield is also needed to support the operational safety case and is the prime input to operational and maintenance doses.

In the JET tokamak, the neutron yield is measured by two systems. The first consists of three pairs of $^{235}U/^{238}U$ fission chambers (KN1), located outside the tokamak in octants 2, 6, 8. The second is the activation system (KN2) allowing to irradiate dosimetric foils in irradiation ends located at the edge of the vacuum vessel. Due to the upcoming second Deuterium-Tritium Experimental Campaign (DTE2) at JET tokamak, they were absolutely calibrated in 2017 [1]. One of the significant challenges during the calibration process of various neutron diagnostics in the JET tokamak was the characterization and deployment of a 14 MeV neutron generator inside the JET vessel, to be used as the neutron calibration source. In order to use the neutron generator as the neutron calibration source detailed characterization work was required. This consisted of a precise estimation of its neutron emissivity including angular, spectral, and temporal distributions. One of the methods used was a dosimetry foil activation method. For the NG characterization campaign, the absolute neutron emission rate of the NG, was estimated with a total uncertainty equal to ±4.0% [2, 3], whilst the neutron emission rate during the in-vessel calibration was assessed with uncertainties ranging from 4.7% for Nb foils to 6.9% for Al foils [1].

Two independent methods, allowing to determine the neutron emission rate of the NG based on the activation results, are presented in this paper. The first method is described in detail in reference [2]. In this case, the neutron emission rate of the NG from monitoring activation results was obtained calculating the activation reaction rates directly in a MCNP calculation, using a developed MCNP model of the NG together with a neutron source routine [4], and with reaction cross sections taken from the International Reactor Dosimetry and Fusion File (IRDFF-1.05) library. In the second case, it was calculated using the FISPACT-II inventory code [5] with neutron flux spectra at the dosimetric foils location and cross section data from the IRDFF-1.05 [6]. Results obtained for both methods have been compared. The impact of the applied cross section library on the neutron emission rates of the NG has been also investigated and presented in this paper. For this purpose, the numerical simulations using FISPACT-II code and cross section data from the Talys-based

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Evaluated Nuclear Data Library (TENDL-2014) have been performed [7].

2. Neutron emission rate of the neutron generator

Two nominally identical neutron generators (type ING-17), selected based on strict criteria [8] and produced by All-Russia Research Institute of Automatics, have been applied as a neutron calibration source. The beam of the NG consists of 50% D and 50% T ions, accelerated to an energy of ≈73 keV, bombards a titanium target containing D/T inside a sealed tube. As a result, beam-target fusion reactions takes place at the target. The main parameters of the selected 14 MeV NG can be found in reference [3], whilst the modelling process of the NG and its beam is described in reference [4] and [9]. Because the intensity of the NG emission may change due to variations in voltage or current, target heating, and neutron generator aging, it should be monitored by compact detectors for research applications. Therefore, two Single Crystal Diamond Detectors (SDD) and activation foils were used for monitoring of the neutron emission during the in-vessel calibration of the JET tokamak neutron monitors. The location of the two monitoring detectors in relation to the NG body is presented in the Fig.1.

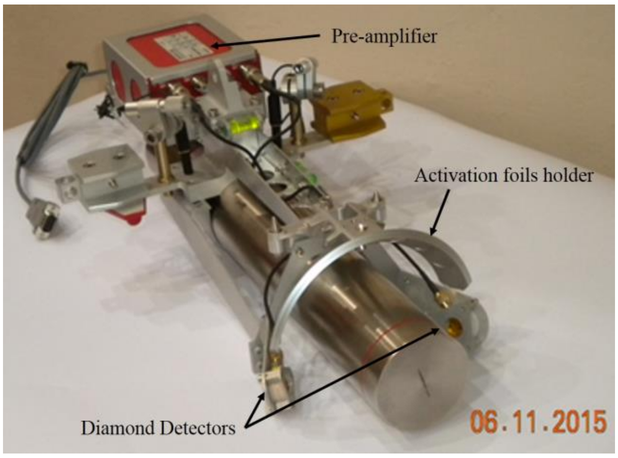

Fig. 1. Picture showing the NG tube, the SDDs and holder containing activation foils at fixed, well-defined positions relative to the NG tube [3].

3. Direct MCNP calculations

The nuclear reactions applied to the monitoring of the NG emission have been selected based on numerous requirements. For example, the cross section for particular reaction should be relatively high, well known, and taken from one of the standard fusion dosimetry libraries. Furthermore, the reaction threshold should be high enough to discriminate the impact of scattered neutrons. When it comes to the reaction products, they should emit intense gamma rays that are readily measurable by gamma spectrometry methods. Other requirements are half-life for the reaction products and the branching intensities of emitted photons. The half-life of the measured nuclide has a practical implication for post-irradiation measurements. The selected nuclear reactions, their parameters, and properties of reaction products are presented in Table 1.

The monitoring foils (four 2 mm Nb foils, four 1 mm Al foils and four 1 mm Fe foils) were irradiated inside the holder attached to the NG both during the NG characterization campaign performed at National Physical Laboratory in Teddington and during the in-vessel calibration of the JET tokamak neutron diagnostics [1-3]. At the end of each day for these campaigns foils were retrieved from the activation holder and transported to the laboratory where they were measured by the gamma spectrometry method. In case of the NG characterization campaign, an HPGe detector (Canberra) was used for the gamma-ray spectrometry measurements. The detector had a relative efficiency of 30% and a full-width half maximum (FWHM) resolution at 1332-keV of 1.8 keV. It was also supplied with numerical characterization, which allows for source-less energy-efficiency calibration. An HPGe detector (ORTEC) with 38% relative efficiency and FWHM resolution of 1.7 keV at 1332 keV was used during the in-vessel calibration of the JET tokamak neutron diagnostics. Details regarding the calibration process and the obtained results are reported in references [1], [2] and [3].

Table 1. Main parameters of selected nuclear reactions and their products [2].

Product of reaction	Half life	Energy of the most intense gamma rays [keV]	Threshold energy [MeV]
^{27}Al(n,p)^{27}Mg	9.46 min	843.8	1.9
^{56}Fe(n,p)^{56}Mn	2.58 h	846.7	3.0
^{27}Al(n,α)^{24}Na	14.99 h	1368.6	3.3
^{93}Nb(n,2n)^{92m}Nb	10.25 day	934.4	9.1

The neutron emission rate of the NG was calculated using a developed numerical code, which is based on the following equation:

$$A_n = \frac{Y_n}{t} \cdot N_T \cdot \langle \varphi(E) \cdot \sigma(E) \rangle \cdot \sum_i B_i \left(1 - exp(-\lambda \cdot t_{Ai})\right) \cdot exp(-\lambda \cdot t_{Ci}) \quad (1)$$

where A_n is the radioactivity of a particular nuclide induced by neutron interactions [Bq], Y_n is the total neutron yield [n], t is the total irradiation time [s], N_T is the number of nuclei in the target sample [nuclei], $\varphi(E)$ is the neutron energy spectrum at the foils location calculated using a detailed MCNP model of the NG together with a neutron source routine [cm^{-2}·s^{-1}], $\sigma(E)$ is the reaction cross section [cm^2] taken from the IRDFF-1.05 library, B_i is a normalization factor [unitless] which takes into account changes in the neutron yield recorded by the diamond detectors during successive NG pulses, λ is the decay constant of the activation product [s^{-1}], t_{Ai} is the irradiation time during particular pulses [s] and t_{Ci} is the subsequent cooling time between pulses.

4. FISPACT-II calculations

In order to validate the neutron emission rate of the NG estimated based on described above methodology, numerical simulations using the FISPACT-II inventory code have also been carried out. The experimental conditions for both the NG characterization campaign and in-vessel calibration of the JET tokamak neutron diagnostics have been fully reproduced. For purpose of the simulations using FISPACT-II inventory code the previously calculated MCNP spectra at the locations of the dosimetric foils and cross section data from the IRDFF-1.05 library have been applied. The obtained neutron emission rates values of the NG were compared to those estimated based on the first method. To investigate the impact of the applied cross section library on neutron emission rate values, the numerical simulations have been repeated using cross sections data from the TENDL-2014 library.

5. Results

The comparison of the FISPACT-II calculated neutron emission rates (C_2) and the results obtained for first method (C_1) and for both NGs is presented in the Fig. 2 and the Fig. 3, while the Fig. 4 shows a comparison of neutron emission rates of the NG estimated for both methods for the case of in-vessel calibration of the JET tokamak neutron diagnostics. Cross sections for all cases are taken from the IRDFF-1.05 library.

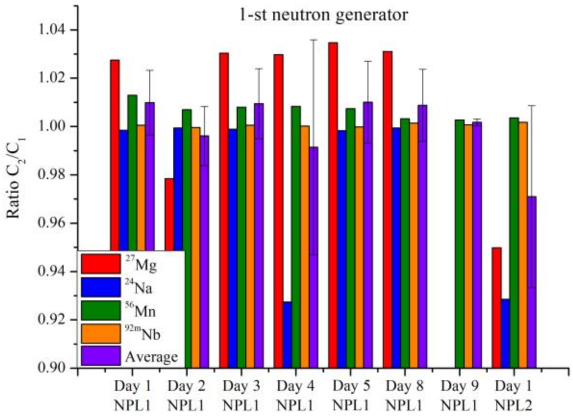

Fig. 2. The comparison of the FISPACT-II calculated neutron emission rates and the values estimated using the first method for 1-st neutron generator and the NG characterization campaign.

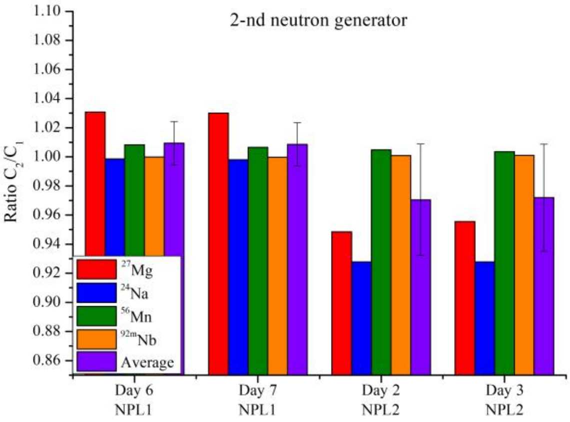

Fig. 3. The comparison of the FISPACT-II calculated neutron emission rates and the values estimated using the first method for 2-nd neutron generator and the NG characterization campaign.

In case of the NG characterization campaign and the neutron emission rates calculated based on ^{27}Mg radioactivity, the discrepancy between the results for both methods was in the range of 3% for first part of the campaign and 5% for the second part of the characterization campaign. When it comes to the neutron emission rate estimated based on radioactivity of ^{24}Na, the discrepancy between results for both methods was in the range of 7% for the second part of the NG characterization campaign and both NGs. This discrepancy was significantly lower during the first part of the NG characterization campaign and equaled to 0.2%. When considering the neutron emission rates calculated based on radioactivity of ^{56}Mn, the high agreement between results for both methods within 1% has been achieved. It is also worth noting the maximal discrepancy for the case ^{92m}Nb was lower than 0.2% for both NGs and whole NG characterization campaign.

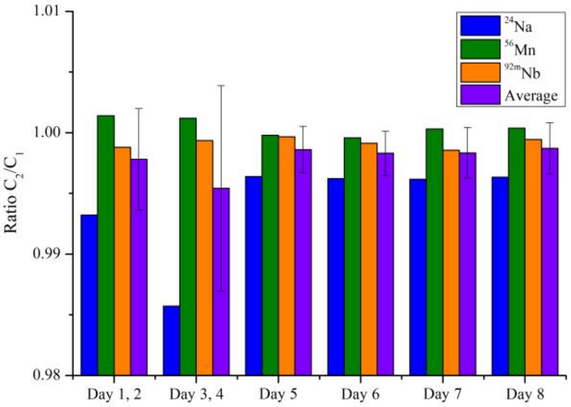

Fig. 4. The comparison of the FISPACT-II calculated neutron emission rates and the values estimated using the first method for the case of in-vessel calibration of the JET tokamak neutron diagnostics.

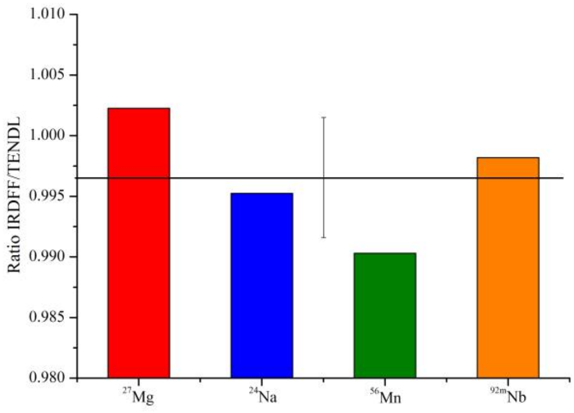

Fig. 5. The impact of the applied cross-section library on the values of the neutron emission rates of the NG.

Regarding the results obtained for the case of in-vessel calibration of the JET tokamak neutron diagnostics, the highest discrepancy was definitely lower than during the NG characterization campaign. The highest discrepancy has been noted for the results for ^{24}Na nuclide and was within 1.5%. For other nuclides the discrepancy was lower than 0.1%.

The comparison of the neutron emission rates values calculated using the FISPACT-II inventory code and applying the cross sections from the IRDFF-1.05 and the TENDL-2014 library is presented in Fig. 5. It is worth noting that the results received for both cross section libraries were almost identical. The biggest discrepancies have been noted for the case of ^{56}Mn radionuclide but they were lower than 1%. The lowest discrepancies observed in the case of ^{92m}Nb radionuclide and they were within 0.2%.

6. Conclusions

The main purpose for the in-vessel calibration of the JET tokamak neutron diagnostics was to estimate the KN1 calibration factors and the calibration factors for ^{93}Nb(n,2n)^{92m}Nb and ^{27}Al(n,α)^{24}Na activation reactions in the KN2 system for a typical DT plasma. The KN1 calibration factor for a DT plasma has been determined with ±4.2% experimental uncertainty, while the calibration factors for ^{93}Nb(n,2n)^{92m}Nb and ^{27}Al(n,α)^{24}Na were estimated with uncertainty within ±6% and ±8% respectively [1]. This uncertainty includes, inter alia, the uncertainty of the neutron emission rate determination measured by monitoring activation foils. Therefore, the proper estimation of the neutron emission rate of the NG is very important.

Two different and independent methods of the neutron emission rate estimation have been described in this paper. The discrepancies between the results obtained for both methods in case of the in-vessel calibration were lower than 1.5%. This shows that both methods of determining the neutron emission rates of the NG are equally reliable and can be used interchangeably, e.g. during future calibrations of neutron diagnostics of the ITER tokamak.

Differences between the size of discrepancies for the NG characterization campaign and in-vessel calibration of the JET tokamak neutron diagnostics resulted from the application of two different types of detectors (Canberra, ORTEC) and two different methods of energy-efficiency calibration [1,2].

It has been shown that the influence of the application of different cross section libraries (IRDFF-1.05 and TENDL-2014) on the neutron emission rates values is insignificant.

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