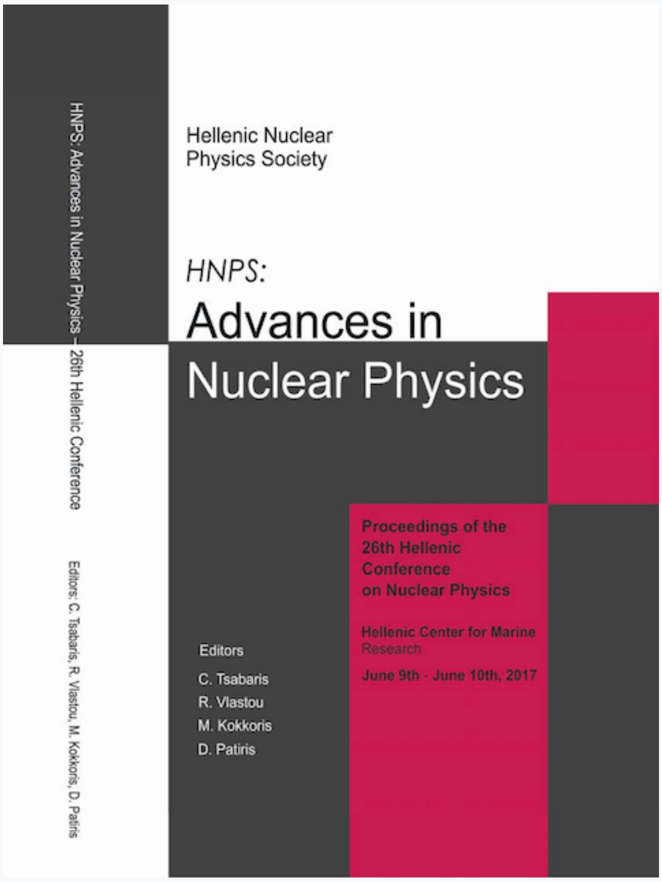
HNPS Advances in Nuclear Physics

Vol 25 (2017)

HNPS2017



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doi: [10.12681/hnps.1967](https://doi.org/10.12681/hnps.1967)

Calibration of activation foils at the 14 MeV Frascati Neutron Generator

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Abstract The calibration of the activation foil detector assemblies used for neutron fluence measurements at the Joint European Torus (JET) is presented. Activation assemblies similar to those used at JET were irradiated at the Frascati Neutron Generator reference Deuterium-Tritium (D-T) neutron field. The activity induced in the foils as well as the neutron and gamma self-shielding correction factors were determined. The results of the study enable to perform accurate neutron fluence measurements in the planned JET D-T campaigns and moreover, contribute to the benchmarking of other experimental techniques and Monte Carlo calculations used for neutron streaming studies at JET and ITER.

Keywords neutron activation, activation foils, calibration, Frascati Neutron Generator, self-shielding

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INTRODUCTION

The Joint European Torus (JET) is the largest operating fusion device and serves as the main risk-mitigation element for the preparation of ITER operation. Neutron fluence measurements are performed at JET in order to validate the numerical tools and data used in ITER nuclear analyses [1, 2]. Previous work has shown that it is difficult to theoretically evaluate neutron fluence along large shielding penetrations in a fusion device [3-6]. Therefore, neutron streaming experiments are planned during the forthcoming JET Deuterium-Deuterium (D-D), Tritium-Tritium (T-T) and Deuterium-Tritium (D-T) campaigns in pursuance of high quality neutron fluence data.

Neutron activation is one of the techniques used to experimentally determine neutron fluence at JET. The method is based on neutron irradiation of selected metallic foils in order to produce radioactive nuclei emitting characteristic gamma rays. Neutron activation provides a robust and unbiased tool for the determination of neutron fluence in a wide range of neutron energies, fluence rates, mixed neutron and gamma ray fields, without mechanical, electro-magnetic and temperature interferences that are encountered in the complex environment of a fusion device [7]. Nevertheless, the activation foil detectors need to be calibrated in known neutron fields that realistically represent the actual measurement conditions.

Aim of the present work was the calibration of the activation foil assemblies used for neutron streaming measurements at JET. The calibration experiment was performed at a reference neutron field provided by the Frascati Neutron Generator (FNG).

EXPERIMENTAL

Activation detectors

The detector assemblies irradiated at FNG were similar to those used at JET in the 2015-2016 D-D campaign measurements [8]. In order to acquire information on the different neutron fluence components (thermal and epithermal), bare and cadmium-covered foils were used. All foils were discs of 14.9 mm diameter and 0.5 mm thickness. In addition to cobalt, tantalum and silver, a thin gold foil was also used. Foils were positioned in two different configurations:
a) in the centre of two polyethylene (PE) moderator cylinders of 25.0 cm in height and 25.5 cm in diameter. In the first moderator (moderator A) both bare and cadmium-covered foils were used, while in the second one (moderator B) only bare foils were used.
b) in a rectangular holder composed of three aluminum slabs of 100 mm × 50 mm × 1.5 mm. The foils were positioned within the middle aluminum slab. In the aluminum box a nickel foil was also placed to detect fast neutrons.

Irradiations at FNG facility

FNG uses a deuteron beam accelerated up to 300 keV impinging on a tritium target to produce a nearly isotropic 14 MeV neutron output via the t(d,n)α reaction or a deuterium target to produce 2.5 MeV neutron through the d(d,n)t reaction [9]. FNG is able to operate either in steady state or pulse mode. To monitor neutron output, the associated particle technique is used, employing an alpha-detector, a fission chamber and a scintillation counter. Moreover, accurate and detailed numerical models of the facility, target and bunker as well as of the neutron source (angular-energy distribution) have been developed [10].

Irradiation of activation detector and B were irradiated sequentially during the first and the second day for 24480 s and 25714 s, respectively. They were both placed exactly in front of the source, along the main axis, with the centre of the PE cylinder at a distance of 15.5 cm from the FNG target. The aluminum holder was placed off-axis, at 90^0 angle and at a distance of 45.0 cm from the FNG target. It was irradiated simultaneously with the moderators, namely for a total irradiation time of 50194 s. The total neutron yield from the source during the irradiation of moderator A, B and the aluminum holder was, according to the monitors, 2.35E+14, 1.83E+14 and 4.18E+14, respectively.

Gamma ray measurements

After irradiation, the detectors were disassembled and the activation foils were measured to determine their activity. The gamma-ray spectrometry system used was based on a high-purity coaxial germanium semiconductor detector (GEM80) of 85% relative efficiency, 1.67 keV energy resolution (Full Width at Half Maximum) at the 1332 keV and a peak-to-Compton ratio of 93:1. All foils were measured at a sample to detector distance of 1 cm for a counting time of 1-4 days depending on their activity levels. The acquired activation spectra were corrected with the corresponding gamma ray background spectrum. Spectrum analysis was performed using Gamma-Vision™ software.

Calculation of activity

The activity of the foil, A_0, at the end of the irradiation period and the foil saturation activity, A_{sat}, were determined using the following equations

$$\mathrm{A}_0 = \frac{C\lambda}{\varepsilon_\gamma\, f_\gamma\, G_\gamma\, f_{TCC}\,(1-e^{-\lambda t_c})\,e^{-\lambda t_d}} \quad (1)$$

$$\mathrm{A}_{sat} = \frac{C\lambda}{\varepsilon_\gamma\, f_\gamma\, G_\gamma\, f_{TCC}\,(1-e^{-\lambda t_c})\,e^{-\lambda t_d}} \times \frac{1}{(1-e^{-\lambda t_{irr}})} \quad (2)$$

where

C is the Net counts registered during the counting time
λ is the decay constant for the product radionuclide
ε_γ is the Full Energy Peak Efficiency (FEPE) for the gamma-ray energy of interest
f_γ is the gamma-ray abundance i.e. the number of gammas emitted per disintegration
G_γ is the gamma self-shielding correction factor for the foil
f_{TCC} is the true coincidence summing correction factor
t_c is the counting time
t_d is the time elapsed between the end of irradiation and the start of counting
t_{irr} is the irradiation time

Correction factor G_γ is defined as the ratio of the detector FEPE for a given foil shape, material and photon energy to the detector FEPE for a point source in air (without foil). The gamma self-shielding factor, G_γ, was calculated using a detailed MCNP model of the germanium detector and foil configuration for the photo-peak energies and foil materials examined in this study.

Correction factor f_{TCC} accounts for the true coincidence effect due to the cascade emission of photons by the measured radionuclides. Correction factors f_{TCC} were calculated for the isotopes of interest using the "TrueCoinc" programme [11].

SIMULATIONS

MCNP code was used to predict the neutron spectra at the FNG irradiation positions as well as to determine the fluence within the volume of each activation foil. Simulations were performed using Monte Carlo codes MCNP5 [12] and MCNPX [13] and cross section data from JEFF 3.1.2 [14] library.

A two-stage simulation approach was employed. In the first stage, a detailed model of the FNG configuration developed by ENEA was used to calculate the neutron fluence and spectrum at the exact positions of the activation assemblies, namely at the centre of the PE moderator (at a distance of 15.5 cm from the FNG target) and within the aluminum box (at 90^o and 45.0 cm far from the FNG target). Subsequently, the neutron spectrum defined at the first stage was used to predict the fluence within each one of the activation foils. It is noted that in the developed MCNP models all the activation assemblies were described in detail, taking into account the material and dimensions of the PE moderator, the aluminum holder, the activation foils and the cadmium covers.

In order to account for the effect of neutron self-shielding in the activation foil material, a correction factor needs to be introduced. The correction factor, f_n, was calculated using MCNP as the ratio of the predicted neutron flux within the volume of the actual foil to the predicted neutron flux over the same volume occupied by air (without the presence of the actual foil).

RESULTS AND DISCUSSION

Activity determination

The experimentally determined activities at the end of the irradiation, A_0, for foils in the aluminum holder and within the PE moderators are presented in Tables 1 and 2, respectively. In these tables, the saturation activity per foil, A_{sat}, as well as the specific saturation activity per neutron, $A_{sat,spec,n}$, (i.e. the saturation activity per g of foil material and neutron emitted from FNG source) are also shown.

The activity values are reported along with their percent relative uncertainties (in parentheses), which include all identified sources of error, namely the counting statistics, detector efficiency, gamma self-shielding, isotope half-life as well as the f_{TCC} and G_γ uncertainties.

As it can be seen from Tables 1 and 2, both in aluminum holder and in moderator A, the decay corrected activities (A_0) of the bare foils are higher than the ones of the Cd-covered foils, as expected.

Foil	Position	Cd-cover	Reaction	A_0 (Bq)	A_{sat} (Bq)	$A_{sat,spec,n}$ (Bq g^{-1} n^{-1})
Ni	Al holder	No	$^{58}Ni(n,p)^{58}Co$	5.41E+00 (10.0)	9.56E+02 (10.0)	2.95E-12 (10.0)
Ag	Al holder	No	$^{109}Ag(n,\gamma)^{110m}Ag$	2.90E-01 (16.7)	1.80E+02 (16.7)	4.67E-13 (16.7)
		Yes		1.62E-01 (22.2)	1.01E+02 (22.2)	2.62E-13 (22.2)
Co	Al holder	No	$^{59}Co(n,\gamma)^{60}Co$	1.26E+00 (10.7)	6.04E+03 (10.7)	1.84E-11 (10.7)
		Yes		3.33E-01 (10.8)	1.59E+03 (10.8)	4.85E-12 (10.8)
Ta	Al holder	No	$^{181}Ta(n,\gamma)^{182}Ta$	1.12E+01 (10.6)	3.20E+03 (10.6)	5.32E-12 (10.6)
		Yes		6.91E+00 (10.7)	1.98E+03 (10.7)	3.30E-12 (10.7)

Table 1. Activities for the FNG foils in the aluminum holder

Foil	Position	Cd-cover	Reaction	A_0 (Bq)	A_{sat} (Bq)	$A_{sat,spec,n}$ (Bq g^{-1} n^{-1})
Au	Moderator A	Yes	$^{197}Au(n,\gamma)^{198}Au$	2.65E+00 (10.7)	3.77E+01 (10.7)	1.23E-10 (10.7)
	Moderator A	No		1.05E+01 (10.5)	1.50E+02 (10.5)	5.31E-10 (10.5)
	Moderator B	No		1.46E+01 (10.5)	1.98E+02 (10.5)	9.04E-10 (10.5)
Ag	Moderator A	Yes	$^{109}Ag(n,\gamma)^{110m}Ag$	3.82E+00 (10.7)	4.86E+03 (10.7)	2.26E-11 (10.7)
	Moderator A	No		3.00E+01 (10.5)	3.81E+04 (10.5)	1.78E-10 (10.5)
	Moderator B	No		2.86E+01 (10.5)	3.47E+04 (10.5)	2.07E-10 (10.5)
Co	Moderator A	Yes	$^{59}Co(n,\gamma)^{60}Co$	2.23E+01 (10.5)	2.18E+05 (10.5)	1.18E-09 (10.5)
	Moderator A	No		1.17E+02 (10.4)	1.14E+06 (10.4)	6.20E-09 (10.4)
	Moderator B	No		8.63E+01 (10.5)	8.06E+05 (10.5)	5.59E-09 (10.5)
Ta	Moderator A	Yes	$^{181}Ta(n,\gamma)^{182}Ta$	1.40E+02 (10.5)	8.20E+04 (10.5)	2.53E-10 (10.5)
	Moderator A	No		1.04E+03 (10.4)	6.07E+05 (10.4)	1.82E-09 (10.4)
	Moderator B	No		5.07E+02 (10.4)	2.83E+05 (10.4)	1.11E-09 (10.4)

Table 2. Activities for the FNG foils within the PE moderators

Neutron self-shielding correction factor

The MCNP calculated neutron self-shielding correction factor, f_n, for the silver, cobalt and tantalum foils included in the PE moderator, was found to be 0.98 ± 0.01, 0.99 ± 0.01 and 1.00 ± 0.01, respectively.

CONCLUSIONS

The activation foil detector assemblies used for neutron fluence measurements at JET were calibrated using the reference D-T neutron field of the FNG facility. The analysis of the experimental data allowed the determination of the activity induced in the foils. Moreover, the gamma and neutron self-shielding factors were determined.

The results of the calibration experiment will enable the implementation of accurate neutron fluence measurements in the planned JET D-T campaign. The implementation of successful campaigns with high quality neutron fluence data is very important since it contributes to the benchmarking of experimental techniques and Monte Carlo simulations used at JET and also allows gaining confidence in the codes used for ITER nuclear analyses and safety assessment calculations.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the EURATOM research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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