VERDI detector benchmark experiment at the ENEA 14 MeV Frascati Neutron Generator

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For future fusion plants, there is a great need for detectors capable to accurately monitor neutrons under the harsh fusion environment. In particular, detectors required in Test Blanket Modules must be capable to accurately measure neutron fluence under high and variable neutron count rates, high gamma background, high temperature, high and variable magnetic fields. The Novel Neutron Detector for Fusion (VERDI) project aims to develop a detector which will provide a robust approach for neutron detection in fusion plants. The detector comprises of a low activation capsule containing a defined concentration of added metallic elements. The neutron fluence and energy spectrum will be inferred by the analysis of the multiple gamma lines produced by the metallic elements activation. In this work, the candidate metallic elements for the VERDI detector are defined. A benchmark experiment with a number of prototype detectors was performed at the ENEA Frascati Neutron Generator under DT operation (14 MeV) to demonstrate the feasibility of VERDI detectors to measure neutron fluence under a reference fusion relevant field. The results of product isotopes gamma-ray measurements are compared to respective calculated data using the FISPACT-II code and a very good agreement is observed.

Keywords: neutron activation, neutron detector, neutron dosimetry, neutron spectrometry, fusion, Ceramic Matrix Composite

1. Introduction

For future fusion plants, such as DEMO, there is a great need for detectors capable to accurately monitor neutrons under the harsh conditions imposed by the fusion environment: high and variable neutron count rates, high gamma background, high temperature and high and variable magnetic fields.

A novel neutron activation detector providing a robust approach for accurate neutron fluence measurements under the harsh fusion environment is being developed under the VERDI project. The detector comprises of a low activation capsule containing a defined concentration of added metallic elements (targets). The neutron detection method is based on the well-known multiple foil activation technique [1, 2]. The neutron fluence and energy spectrum can be inferred by the analysis of the gamma lines produced by the activation reactions in the metallic elements employing a computational unfolding procedure. The key novelty is provided by the robust capsule matrix which is enabling measurements to be performed under the harsh conditions encountered in a fusion plant.

The proposed detector allows the monitoring of the integral neutron fluence and the reconstruction of the neutron energy spectrum at the position of the measurement. Therefore it will allow monitoring the neutron fluence on components and materials, tritium breeding rates, nuclear heating, and a variety of other parameters in fusion reactors such as ITER and DEMO, as well as future fusion plants [2 – 5].

In this work the selection of the active metallic elements to be included in the VERDI detector and the capsule material is discussed. A set of prototype detectors were fabricated and tested at the ENEA Frascati Neutron Generator (FNG) with DT neutrons (14 MeV) in order to demonstrate the feasibility to measure neutron fluence in a fusion relevant neutron spectrum. The results of this experiment are presented are compared to respective computational results calculated using the FISPACT-II inventory code [6].

2. Method

2.1 Candidate metallic elements selection

The selection criteria for the active metallic elements were their activation cross-section (radiative capture, threshold reactions), product half-life, melting point, intensity of emitted gamma lines, interferences between gamma lines, material hazard information and cost. The most promising candidate metallic elements that fulfill these criteria are presented in Table 1 together with respective physical and nuclear characteristics. For the experiment at the ENEA FNG facility active metallic elements in the form of Ø10.0 mm foils were used.

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Table 1. Candidate metallic elements and their properties

Element (Melting point)	Reaction	$E_{threshold}$ (MeV)	Product $T_{1/2}$	E_γ (keV)	Yield (%)
Ag (962°C)	^{107}Ag (n, 2n) ^{106m}Ag	10.00	8.28 d	717.3	28.9
Au (1064°C)	^{197}Au (n, γ) ^{198}Au	--	2.69 d	411.8	95.5
	^{197}Au (n, 2n) ^{196}Au	8.13	6.18 d	355.7	87.0
Mn (1246°C)	^{55}Mn (n, 2n) ^{54}Mn	10.50	310 d	834.8	100.0
Nb (2469°C)	^{93}Nb (n, 2n) ^{92m}Nb	9.00	10.15 d	934.5	99.1
Ni (1455°C)	^{58}Ni (n, p) ^{58m}Co	0.40	9.04 h	×	
	^{58m}Co (IT) ^{58}Co	--	72 d	810.8	99.4
	^{58}Ni (n, np) ^{57}Co	9.24	271.8 d	122.1	85.6
	^{58}Ni (n, 2n) ^{57}Ni	12.42	35.6 h	127.2	16.7
Rh (1963°C)	^{103}Rh (n, 2n) ^{102}Rh	9.50	2.9 y	475.1	38.4
	^{103}Rh (n, p) ^{103}Ru	0.20	39.3 d	497.1	90.9
Ti (1668°C)	^{46}Ti (n, p) ^{46}Sc	1.62	85 d	889.2	100.0
	^{47}Ti (n, p) ^{47}Sc	0.66	3.43 d	159.4	68.0
	^{48}Ti (n, p) ^{48}Sc	3.29	44 h	983.5	100.0
Y (1526°C)	^{89}Y (n, 2n) ^{88}Y	12.00	106.6 d	1836.1	99.2
Zn (419°C)	^{64}Zn (n, 2n) ^{63}Zn	12.50	38.5 min	669.6	8.0
	^{66}Zn (n, 2n) ^{65}Zn	11.32	244.26 d	1115.6	50.0
	^{68}Zn (n, γ) ^{69m}Zn	--	13.76 h	438.6	94.8

2.2 Candidate capsule material and design selection

For the construction of the VERDI detectors, the metallic elements are to be enclosed in a capsule with (i) resistance to high temperatures (ii) ability to introduce metallic elements in a robust construction and (iii) very low concentration of impurities that can be activated and interfere with the target elements gamma lines.

The materials that meet the specifications were graphite and Ceramic Matrix Composite (CMC). The former was supplied by Goodfellow and the latter (a carbon fiber reinforced silicon carbide – C/C-SiC) by DLR-German Aerospace Center. Some typical properties of the matrix materials are presented in Table 2 [7, 8].

Table 2. Typical properties of candidate matrix materials

Properties	Graphite	C/C-SiC
Maximum working temperature	neutral or reducing atmosphere: 3000 °C	1600 °C
Machinability	easily machinable	requires diamond tools
Porosity (%)	0.7 - 53	2 - 5
Tensile strength (MPa)	6.2	80 - 190
Young's modulus (GPa)	8 - 15	50 - 70

The detector capsule is composed of two parts: a base and a cover (Fig. 1), which are joined using an inorganic high temperature graphite-based adhesive Graphi-Bond 669, supplied by Aremco Products. The adhesive joining was selected rather than mechanical joining, mainly due to high efficiency in thin plates bonding, minimization of the capsules structural weight, which in turn results in the minimization of the neutron flux attenuation and in the simplicity of the capsule geometry requiring minimum machining processing.

The dimensions of the prototype detectors used at the FNG experiment are presented in Fig. 2.

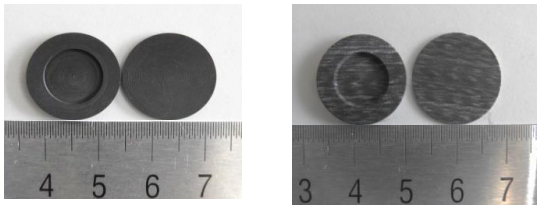
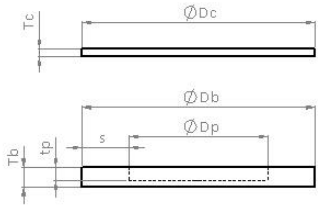


Fig. 1. VERDI capsule components (base, cover) fabricated from Graphite (left) and CMC (right)



Dimensions (mm)	
$D_c = D_b$	17.5
T_c	0.5
D_p	10.5
s	3.5
t_p	1.0
T_b	1.5

Fig. 2. Schematic and dimensions of the prototype detectors used at the FNG experiment

2.3 Irradiation of prototype VERDI detectors at the ENEA FNG facility

In total six prototype detectors were tested at the FNG facility. Two detectors of each type of matrix contained foils and one was blank. For discrimination, a code number was given to each detector (Fig. 3). Detectors No.2 and No.5 are the blank detectors.

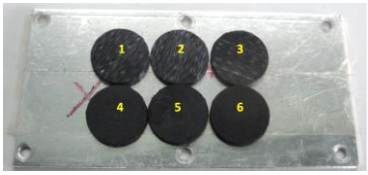


Fig. 3. The different irradiated prototype detectors (up: CMC matrix, down: graphite matrix)

For the irradiation, the prototype detectors were placed on an Al holder (99.0% purity, 100 mm width, 50 mm height, 1.5 mm thickness), allowing the precise alignment of the detectors with respect to the neutron beam (Fig. 4). The detectors were irradiated for 4.506 h at 5.413 cm distance (5.113 cm air, 0.1 cm stainless steel, 0.1 cm H_2O and 0.1 cm Cu) from the source.

Fig. 4. The irradiation position at the FNG facility

The neutron source strength at the FNG target is determined absolutely by counting the α-particle associated with the neutrons produced by the D-T reaction. Using this technique, the achieved total neutron yield at the source was measured to 7.29×10^{14} neutrons. Taking into account the MCNP model of the source (§2.4), the neutron flux at the detectors' irradiation position ranged from 1.20×10^{8} to 1.34×10^{8} n/cm^2/s.

After the irradiation, the prototype detectors were analyzed by means of gamma spectrometry in two stages. First, the detectors were measured at ENEA immediately after the end of irradiation (60% rel. eff. HPGe), to detect the relatively short-lived product isotopes. Then, the detectors were transferred and measured at NCSRD (85% rel. eff. HPGe), aiming the detection of additional peaks corresponding to isotopes with longer half-lives: ^{57}Co, ^{58}Co, ^{102}Rh, ^{103}Ru, ^{92m}Nb.

2.4 Simulations of the VERDI detector irradiations

Radionuclide inventory calculations were performed using the FISPACT-II code [6], which is developed by the CCFE and predicts how materials evolve under irradiation and through radioactive decay processes. The EAF-2010 nuclear data library was used with VITAMIN-J 175 group energy bin structure [9].

Calculations were also performed using the MCNP5 code [11], for the ENEA FNG quasi mono-energetic neutron field [10] including the detailed VERDI detectors irradiation geometry. No significant differences were observed in the simulated neutron spectra because of the different positioning of the detectors.

3. Results

3.1 Gamma spectrometry results

Induced activity was calculated for all detectors at the end of irradiation. For each isotope the weighted activity was calculated based on each detected photopeak. The comparison of the results showed good agreement between the different detectors for all isotopes (Fig. 6). It should be noted that ^{198}Au was not detected in the analysis of VERDI detector No.6 because of the isotope decay between the end of the irradiation and the start of the measurement at NCSRD.

Regarding the blank detectors, no induced activity was detected, apart from the peak of ^{24}Na which is not used as product isotope of interest. This was attributed to the Al impurities in both the foils and the adhesive used, producing ^{24}Na through the reaction ^{27}Al (n, α) ^{24}Na. In addition, photopeaks of ^{48}Sc were detected the CMC blank capsule, yet in very low concentration compared to the induced activity in the VERDI detectors containing foils (1 Bq compared to ~400 Bq).

The experimental induced activities were compared to calculated results using the FISPACT-II code. The ratio of calculated to experimental data (C/E) for each isotope is presented in Fig. 7. The uncertainties include the experimental component and the component due to the cross section data, as given by FISPACT-II. The experimental uncertainties are generally lower than 15%, while the uncertainty of the calculated value varies between 10% and 30%. Higher uncertainties are observed for ^{198}Au and ^{47}Sc (~40%). Taking into account the individual C/E ratios, the overall weighted C/E ratio for all isotopes was calculated to be 1.00 ± 10.0% (1σ).

3.2 Reconstruction of the neutron spectrum

Neutron spectrum unfolding using the VERDI detectors experimental data is discussed in detail in reference [12]. In this work, the FNG experimental data were employed for the reconstruction of the neutron spectrum using the MAXED code [13].

The inferred spectrum using the MAXED code is presented in Fig. 5 along with the MCNP calculated spectrum. It can be concluded that there is generally good agreement between the two spectra; however the unfolded spectrum presents an overestimation of the neutron fluence of ~60% at the peak. Further work is needed in order to improve the convergence between MAXED and the initial neutron spectrum estimate.

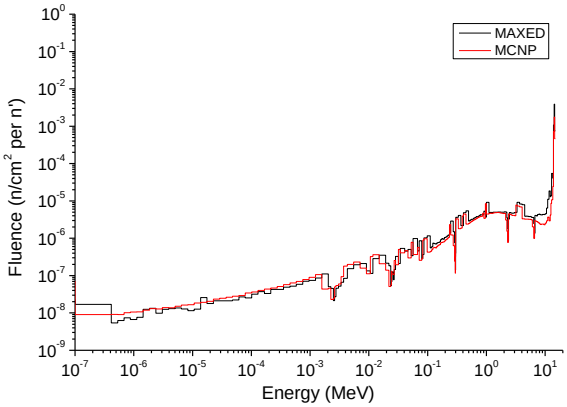


Fig. 5. Comparison of FNG neutron spectra using MAXED unfolding code and MCNP code

4. Conclusions

A number of prototype VERDI detectors was fabricated and tested at the ENEA FNG facility to demonstrate the feasibility of the VERDI detector to measure neutron fluence in a fusion relevant neutron spectrum. The experimental data were compared to respective calculated data using the FISPACT-II code and a very good agreement was observed. The overall ratio of the calculated to experimental data (C/E) was found to be 1.00 ± 10.0% (1σ).

It was shown that the complexity of the gamma spectra from the activation products is disentangled by careful selection of active elements in order to have minimum overlapping of the emitted photons. Moreover, interference from the capsule material was found to be minimal. The experimental data provided the necessary information for the reconstruction of the neutron spectrum using the MAXED code. Preliminary results of the inferred spectrum were provided in this work and are very promising. Further work using more elaborate spectrum unfolding techniques is now in progress [12].

The methodology is expected to be further refined, through additional experiments in the fusion environment of the Joint European Torus (JET) tokamak during the forthcoming campaigns, as well as in the fission environment of a nuclear research reactor.

Acknowledgments

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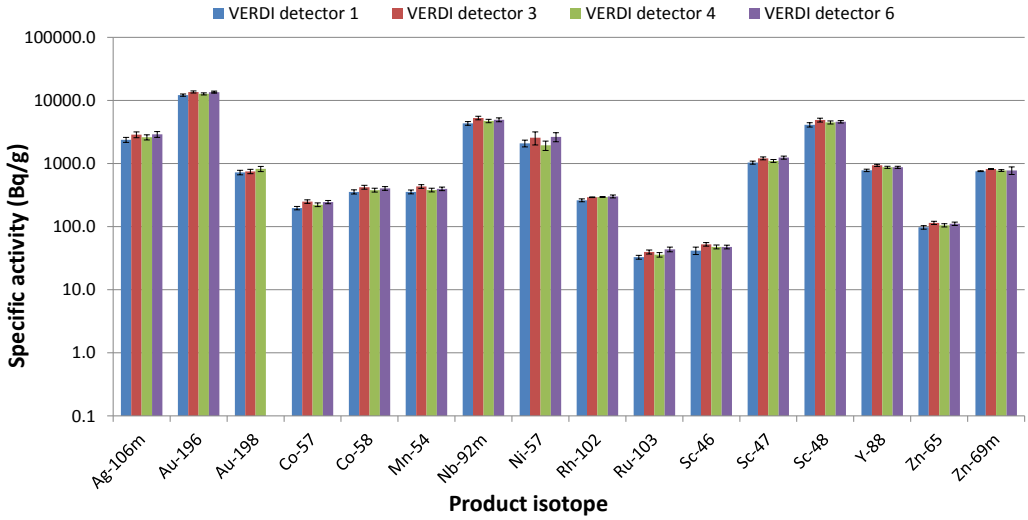

Fig. 6. Comparison of the specific activity of the different VERDI detectors

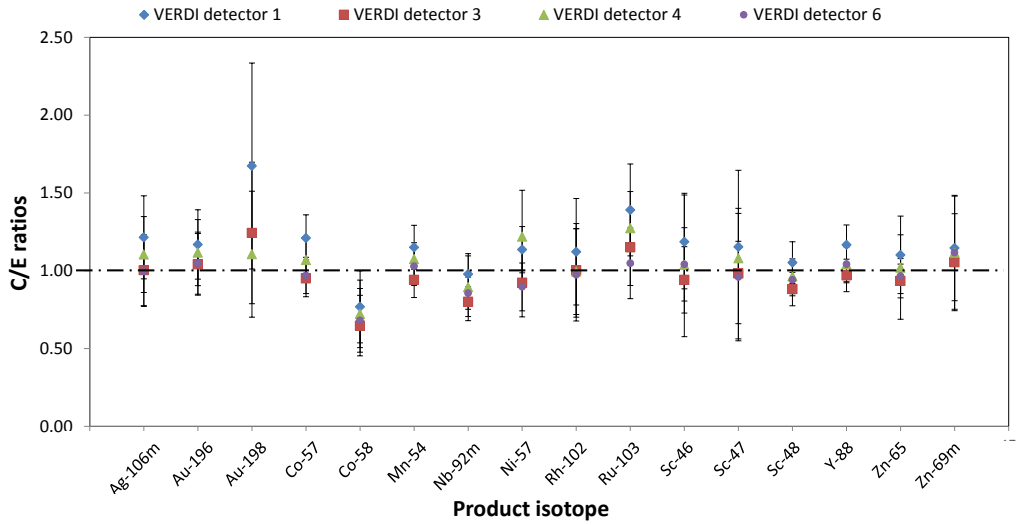

Fig. 7. Weighted C/E ratios for each product isotope

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