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Benchmark Experiment for the Validation of Shut Down Activation and Dose Rate in a Fusion Device

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A neutronics experiment has been performed at the 14 MeV Frascati Neutron Generator (FNG) and using a proper experimental set-up, with the objective to validate the calculations of shut down dose rate outside the ITER vacuum vessel. In the experiment, a shield mock up was irradiated for sufficiently long time that the level of induced activation was followed after shut down by dosemeters for a cooling time as required for allowing personal access. The measurements were analysed using a rigorous, standard two-step method (MCNP transport / FISPACT inventory codes), and a new one-step method with an *ad hoc* modified version of MCNP code, developed within the ITER Project to provide a more straightforward tool for dose rate analysis outside the vessel. The results of the experiment are presented together with the analysis performed with both approaches and with different nuclear data.
KEYWORDS: fusion reactor, shut down dose rate, benchmark experiment, nuclear data validation

I. Introduction

Nuclear analyses for the design of fusion devices like ITER are based on calculations with inherent uncertainties, mainly due to nuclear data uncertainty and to the approximations introduced in the modelling of complex and large geometries. Previous experiments have provided validation of nuclear performance of ITER shielding system, [1,2]. However, within the safety relevant problems, present dose rate calculations for such geometries still suffer from uncertainties which may be unacceptable for guaranteeing occupational safety during hands-on maintenance inside the cryostat. Experimental validation is, therefore, needed.

To this purpose, a neutronics experiment has been performed using the 14 MeV Frascati Neutron Generator (FNG) and a proper experimental set-up, in which a neutron spectrum was generated similar to that occurring in the ITER vacuum vessel, compatibly with the intensity of the available neutron source and its capability to induce sufficiently high dose levels in the shield mock-up.

The mock-up was irradiated at FNG for sufficiently long time to create a level of activation which was, after shut down, followed by dosemeters for a cooling time assumed to be required for allowing personal access: the dose rate was measured in a continuous way inside the cavity for more than two months after shut down. Other related and useful quantities were measured as well, like the dose distribution and the activation rates of Ni-58(n, p), producing Co-58 responsible of most of the dose rate in the relevant decay time, and of Ni-58(n,2n) which produces Ni-57, the second most important contributor to total dose rate in the first week after shutdown, after Mn-56 is decayed. The experiment was analysed using two different approaches: 1) a rigorous, standard two-step method, i.e. using MCNP-4B transport code with FENDL/MC-2.0 neutron cross section library and FISPACT inventory code with FENDL/A-2.0 activation cross sections, and 2) a new one-step method with an *ad hoc* modified version of MCNP code and cross section libraries, developed within the ITER Project to provide a more straightforward and quick tool for dose rate analysis outside ITER vessel, [3,4]. This MCNP version uses *ad hoc* libraries in which the cross sections are taken from FENDL-2.0: both FENDL/MC-2.0 and FENDL/A-2.0 were used to calculate the production of relevant nuclides.

The results of the experiment are presented in the paper together with the analysis performed with both analytical approaches and with different nuclear data.

II. Measurements

The experimental assembly consisted of a block of stainless steel and water equivalent material (100 cm x 100 cm, 71.4 cm thick), with a cavity (behind about 22.47-cm-thick shield), and a channel in front of the cavity to include the effect of a streaming path in the bulk shield (**Fig.1**). The mock-up was irradiated by 14-MeV neutrons at FNG, for a total of 18 hours during three irradiations in three days. The total neutron production was 1.815×10^{15}.

The dose rate measurements inside the cavity were carried out using a Geiger-Müller detector (G-M, Mod. 7312 from Vacutec Company) with a Multi-Channel Scaler (MCS) with variable dwell time (from EG&G Ortec). The size of the G-M detector was 12 mm in diameter, 80 mm in length. Measurements by G-M tube were taken in the centre of the cavity (Fig. 1), in front of the open channel, starting just after the FNG shut-down to obtain the dose rate versus time from half an hour to more than two months of cooling time. The total experimental uncertainty was ± 10%. The quoted error accounts for several contributions (summed by quadratic law): statistics and background (<±5%), calibration (<±5%), dead time (<±2%), energy dependence (±5%) and angular dependence of the G-M response (±5%).

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The dose rate in the cavity centre was also measured by high sensitivity thermoluminescent detectors of the type TLD-300 (CaF_2:Tm) from Harshaw Company and Chinese GR-200A (LiF:Mn, Cu, P). The TLDs were chosen, since they allow a complete independent dose rate measurement

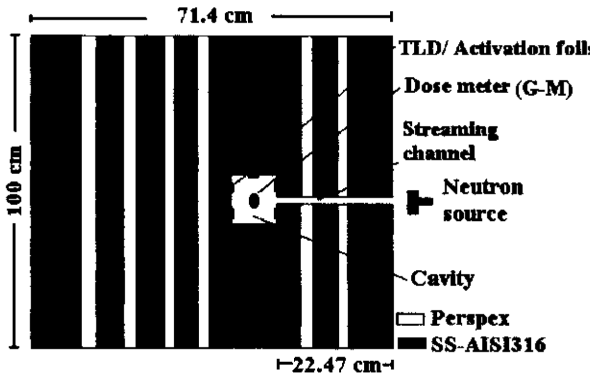

Fig. 1 Schematic view of the experimental set-up (vertical section) and of location of detectors (Geiger-Muller dose meter, TLD, and Ni activation foils) in the cavity inside the stainless steel/perspex mock-up

although they are used just at the limit of their response range. The total error associated with the measurement is ±17%. The contributions to the error come from statistics (between ±5% and ±8%), background (±14%) and calibration (±5%). Measurements were carried out at four decay times locating four TLDs of each type, enclosed in a polyethylene holder 1-mm thick, close to the G-M dosimeter for time intervals ranging from 18 to 22.5 hours. **Figure 2** shows the measured dose rate in the centre of the cavity versus cooling time (after background subtraction), both for G-M and for TLD detectors. The comparison of the results obtained with the two techniques is in agreement within 12%, well within the combined experimental uncertainties.

The same TLD were used to measure also the dose rate distributions in several locations inside the cavity (on the walls as shown in Fig.1).

Ni-58(n,p)Co-58 and Ni-58(n,2n)Ni-57 activation reaction rates during irradiation were measured by Ni foils located all around the cavity walls (Fig. 1). The goal was to measure independently the production of Co-58, which is responsible of most of the dose rate in the relevant decay time, and of Ni-57 which is the second most important contributor to total dose rate in the first week after shut-down, when Mn-56 has decayed (see **Fig. 3**). The total experimental error was ±4.5% and it results from several contributions coming from FNG neutron source uncertainty (±3%), counting statistics (<±2%) and detector (HPGe) absolute calibration (±2.5%).

III. Analysis and Results

The experiment was analysed (1) with a rigorous two-step (R2S) method which makes use of the MCNP transport code [5] and the FISPACT inventory code, [6] and (2) with a direct one-step method (D1S) using an *ad hoc* modified version of MCNP, [3,4], where neutron and decay gamma transport are handled in one single Monte Carlo calculation run. In either approach, cross-section data from the FENDL/MC-2.0 (Monte Carlo transport), [7] and FENDL/A-2.0 (activation), [8] were used.

Two different MCNP models of the FNG assembly were employed in the R2S method: one for the neutron transport calculation during irradiation and the other one for the decay gamma transport calculation after irradiation. In this way proper account is taken of the fact that during the irradiation the central cavity was empty and the lateral access was plugged whereas after irradiation the plug was removed and the detectors were inserted into the cavity. In the R2S approach, the neutron flux spectra are calculated in the VITAMIN-J 175 group structure for the cells of the "FNG irradiation model" and are input to FISPACT. Activation inventories and decay gamma sources (spectrum and intensity) are then calculated for each cell making use of the associated neutron flux spectra. This requires one FISPACT-calculation per cell and material taking into account the proper irradiation history. The resulting decay gamma source distribution is then routed back to MCNP with the "FNG shut-down model".

The D1S method assumes that a radioactive nuclide generated during irradiation promptly emits the associated decay gammas. Neutron and decay gamma transport then can be treated in one single Monte Carlo calculation run. On the basis of this assumption, a special version of the MCNP code has been developed at ITER JCT making use of ad hoc data libraries in which the cross sections are taken from FENDL-2.0. Both FENDL/MC-2.0 and FENDL/A-2.0 have been used with this method to calculate the production of the relevant radioactive nuclides. Decay gamma spectra and yields are taken from EAF-99, [9]. When calculating the dose rate, adjustment factors have to be applied to account for the proper decay rate of a specific radioactive nuclide at the considered decay times taking into account the actual irradiation history.

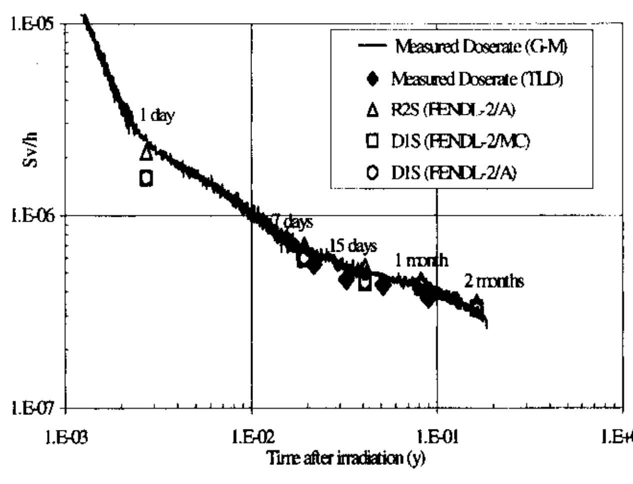

Fig. 2 Comparison between measured and calculated dose rate in the cavity centre.

In the D1S calculation, the FNG assembly model with inserted detectors and removed plug was employed as it is not possible in this approach to use two different models for the irradiation and the shut-down period.

Figure 3 shows the contributions of major nuclides to the

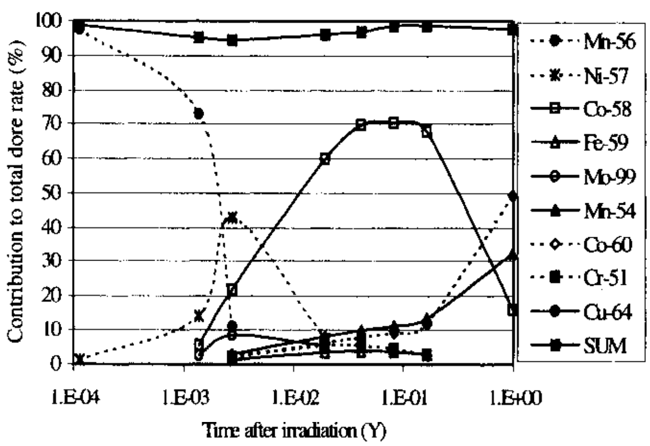

Fig. 3 Contribution of most relevant radioisotopes, normalised to the total contact dose rate, at the cavity wall. The sum is also shown

total contact dose rate, as calculated by FISPACT at the inner cavity wall. Mn-56 dominates at short times (i.e. t<1 d), Ni-57 at around 1 d, and then Co-58 dominates in the time range of practical interest for allowing personal access for maintenance purposes. The nuclei considered in the figure contribute to more than 95% of the total dose rate, as shown in the same figure by the sum line.

The experiment analysis has been carried out by the R2S method for cooling times from 1 day to 2 months, the results are also given in Fig. 2 (Δ). The statistical uncertainty in the MCNP calculations is always less than 2%, both in the calculation of neutron fluxes and in that of gamma dose rates. The analysis was performed with the D1S method for the same cooling times (also in Fig.3): the production rate of radioactive nuclides was calculated both using FENDL/A-2 (O) and FENDL/MC-2.0 ( ). The statistical uncertainty ranged between 4 and 6%. The nuclides considered were Mn-56, Co-58, Ni-57, Mo-99, Mn-54, Cr-51, Fe-59 and Co-60, Cu-64 (the same as given in Fig 3).

The total uncertainty on the comparison was ≤ ±12%, obtained summing by quadratic law the uncertainty on the measured values E (±10%), that on the calculated values C, and the uncertainty on the FNG source calibration (±3%). C/E ratios with uncertainties are shown in **Fig. 4.**

With the R2S method, C/E values are found close to unity within the total uncertainty in the comparison for decay times ≥ 7 days, while underestimation order of 15% is found for shorter times, which can be addressed to Mn-56 and Ni-57. This uderestimation is more pronounced when using the D1S method, in part due to the fact that in this case minor nuclides, contributing to the total dose rate at the percent level, are not considered.

The analysis of dose rate distribution measurements on the cavity walls by TLD detectors has been carried out with the R2S method (stat. unc. ≤3%) and with the D1S method (stat. unc. 3% - 8%). The dose rate distribution is a strong function of the position in the cavity because of the presence of the open channel in front of the neutron source. The TLD capsules and positions were exactly described in the MCNP

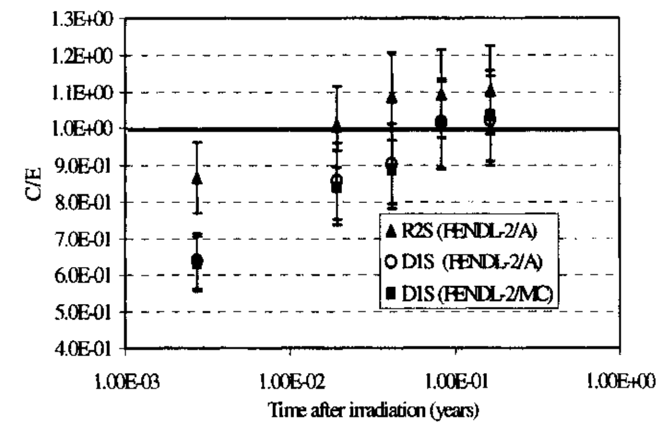

Fig. 4 C/E values for the dose rate measured by G-M detector

model, as shown in Fig. 1. An example of results is given in **Fig. 5**, were the calculated dose rates are compared with the measured ones (indicated by squares) for the TLD located close to the streaming channel (position 5). Generally a good agreement is found with the experimental data with both R2S and D1S methods within the total uncertainties: the features of the dose rate distribution inside the cavity are satisfactorily predicted by both calculations. However, a trend to overestimate by calculation is observed at decay times ≥ 15 days, consistently with what is observed in the analysis of the dose rate in the cavity centre.

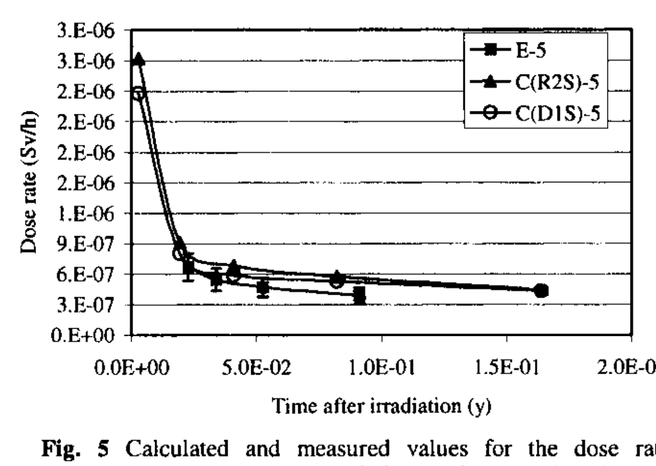

Fig. 5 Calculated and measured values for the dose rate measured by TLD on the cavity wall close to the streaming channel

The neutron flux at the Nickel foils during irradiation was calculated using MCNP, the Ni-58(n,p)Co-58 and Ni-58(n,2n)Ni-57 reaction rates were calculated 1) using a procedure similar to the R2S method, i.e. calculating the Ni activation by FISPACT taking the Ni-58(n,p) or (n,2n) cross sections from FENDL/A-2 (stat. unc. of the MCNP flux calculations ≤ ±2.5%) ; and 2) using a procedure similar to the D1S method, i.e. calculating the Ni activation directly in the MCNP run taking the Ni-58(n,p) and Ni-58(n,2n) cross sections from the dosimetry file IRDF-90.2, [10] and from FENDL/MC-2 (stat. unc. $\leq \pm 2.5\%$). All results are given in **Fig. 6** and **7**. For the Ni-58(n,p) reaction, using FISPACT with FENDL/A–2 (R2S), C/E values are in general slightly higher than unity, while those obtained with direct MCNP calculation (D1S) using IRDF-90 and FENDL/MC–2 are generally lower and in better agreement with the measurements. For the Ni-58(n,2n) reaction, using the direct MCNP calculation (D1S) with IRDF-90 and FENDL/MC–2, C/E values are very close to unity. Using FISPACT with FENDL/A–2 (R2S), C/E are about 1 - 3% lower than in the previous case.

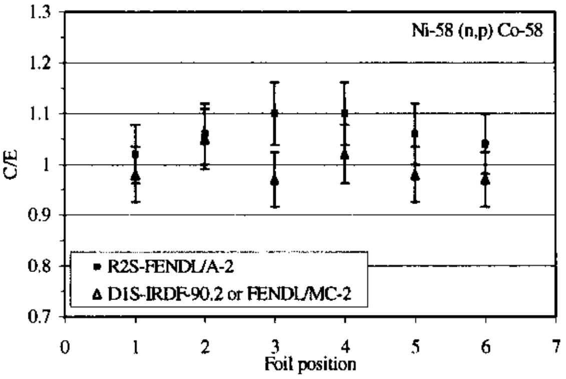

Fig. 6 C/E values for Ni-58 (n,p)Co-58 reaction

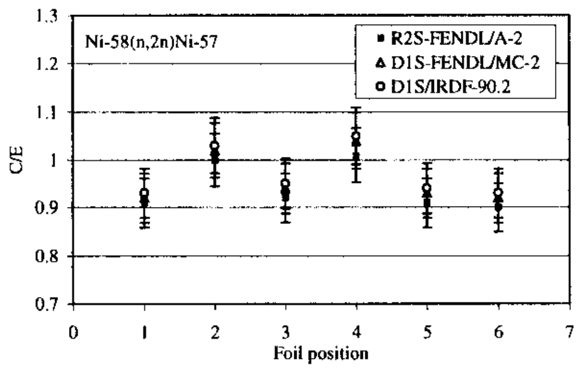

Fig. 7 C/E values for Ni-58 (n,2n)Ni-57 reaction

IV. Discussion and Conclusions

The dose rate calculated with both R2S and D1S method agrees with the measured one in the cavity centre within the total uncertainty in the comparison ($\pm 12\%$) for decay times > 7 days, although showing a slight overestimation likely due to the Co-58 production cross-section. Underestimation order of 15% is found with R2S for shorter times which can be addressed to Mn-56 and Ni-57. This underestimation at short decay times is more pronounced when using the D1S method (up to 30%), in part but not completely due to the fact that in this case minor nuclides, contributing to the total dose rate at the percent level, are not considered.

The activation reactions contributing most to the dose rate in the relevant decay times, i.e Ni-58(n,p)Co-58 and Ni-58(n,2n)Ni-57, were also measured directly inside the cavity using activation foils and analysed using the same methods as for the dose rate. For the Ni-58(n,p)Co-58 activation measurements the R2S method gives C/E values slightly higher than unity, while the C/E values obtained with the D1S method using IRDF-90 and FENDL/MC–2 are in better agreement with the measurements. For the Ni-58(n,2n)Ni-57 reaction, both methods give C/E values slightly lower than unity. These results are coherent with those found in the analysis of the dose rate by the R2S and D1S methods.
These results show that in the case of ITER, the shut down dose rate outside the vessel can be calculated by both R2S and D1S methods within $\pm 15\%$ uncertainty from a few days after shut down to about 2 months of cooling time.

Aknowledgements

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