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Radiological characterization of ITER materials

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Abstract Samples of ITER materials were irradiated at the Joint European Torus (JET) to study their activation properties under neutron irradiation in a real fusion environment. The samples were irradiated at JET during the 2021 Tritium-Tritium (T-T) and Deuterium-Tritium (D-T) plasma experimental campaigns, with neutron flux levels and energy spectra comparable to the ones expected at ITER, and then distributed to European labs for gamma-spectroscopic measurements. In this work, the methodology of gamma-spectroscopic analysis performed at NCSR D is presented. The activated samples were measured using a high purity germanium detector to identify the produced radionuclides and quantify their induced activity levels. Correction factors, calculated using the MCNP code and the TrueCoinc program, were applied to account for the effects of self-attenuation of photons within the sample and true-coincidence summing in the detector, respectively. This work provides experimental data on the activation properties of materials used in ITER, which is important for the radiation protection of personnel and the safe handling of activated reactor components during maintenance activities, as well as for the decommissioning planning of ITER materials and their safe disposal as waste or for recycling.

Keywords Fusion materials, gamma spectroscopy, activity determination, correction factors

INTRODUCTION

Experiments are being performed at the Joint European Torus (JET), in the UK, aiming to investigate the neutron activation properties of ITER materials, namely materials that are used in ITER either as structural or as functional components, under neutron irradiation in a real fusion environment [1]. Radiological characterization of industrial materials used in ITER is of outmost importance for the radiation protection and safety of personnel during ITER operation, repair and maintenance, as well as for radioactive waste management after the end of its operational phase.

Selected ITER materials were irradiated during the 2021 Tritium-Tritium (T-T) and Deuterium-Tritium (D-T) plasma operations at JET. After completion of the irradiation, the activated materials were shipped to several European labs for gamma spectrometry. The present study discusses the methodology of gamma-spectroscopic analysis performed at NCSR D to determine the levels of induced activity and identify the main radionuclides contributing to the activation of each material.

EXPERIMENTAL

Samples

The set of samples studied at NCSR D comprised 17 pieces of materials used in ITER, including various steels, alloys, tungsten, Inconel and Eurofer, sourced from various manufacturers, as well as two cobalt and two nickel dosimetry foils. The detailed list of the samples measured, as well as the respective manufacturer is presented in Table 1. All samples were disc-shaped foils of 18 mm in diameter and 0.5 mm in thickness, with masses that ranged from 0.35 to 1.13 g. The total activities of the samples, measured upon receipt of the sample packages at NCSR D, varied from 1.2E4 to 2.0E5 Bq.

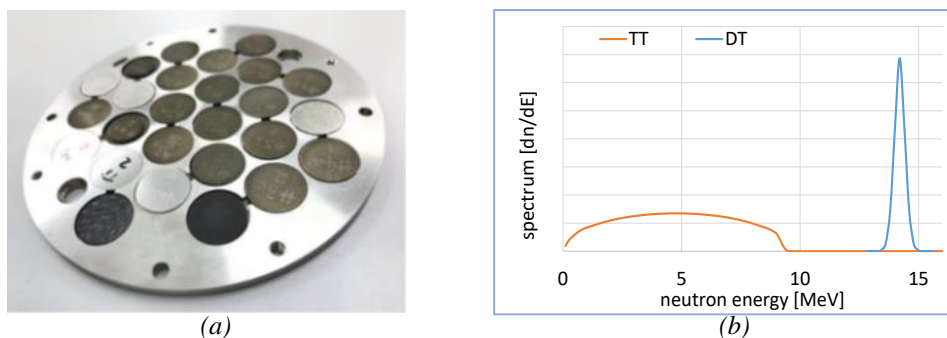
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Table 1. *Samples studied at NCSR*

Sample code	Material (manufacturer)
ITER #1	SS316L(N)-VV plate (Industeel)
ITER #2	SS316L(N)-VV plate (R. Kind)
ITER #3	SS316L(N)-VV plate (Thyssen)
ITER #4	SS316L(N)-TF radial plate 2500/64
ITER #5	SS316L(N)-TF radial plate 2500/68
ITER #6	SS316L(N)-TF radial plate 2501/33
ITER #10	Divertor Alloy 660
ITER #11	Divertor Alloy 660
ITER #14	Divertor W monoblock
ITER #15	Divertor W monoblock
ITER #16	Divertor XM-19
ITER #18	Inconel 718
ITER #19	Eurofer 97-3
ITER #23	In-wall shield SS304L
ITER #24	In-wall shield SS304L
ITER #25	PF Jacket SS316L
ITER #27	Divertor Nadege SS316L
Dosimetry foils	Co
Dosimetry foils	Ni

Irradiation

The samples were placed in a suitable holder (Fig. 1a) and irradiated at the JET Long Term Irradiation Station (LTIS), in a location very close to the plasma source, during both T-T and D-T campaigns from March to December 2021. The neutron flux levels and energy spectra were considered to be similar to those anticipated at ITER, resulting in a total neutron yield of 8.59×10^{20} neutrons. The MCNP calculated spectra of source neutrons, corresponding to the T-T and D-T reactions in the plasma, are shown in Fig. 1b [2]. As seen in Fig. 1b, the T-T reaction produces a continuum of neutron energies ranging up to about 9 MeV, while the D-T neutrons exhibit a spectrum with a peak at 14.1 MeV.


Figure 1. (a) *Sample Holder* (b) *MCNP calculated spectra of T-T and D-T source neutrons (from ref [2])*

Gamma spectrometry

Gamma measurements were performed using a High Purity Germanium detector (GEM80) of 85% relative efficiency and 1.85 keV energy resolution at the 1332 keV ^{60}Co photopeak. In order to decrease the elevated detector dead times arising from the high sample activity levels, the samples were placed at a distance of 12 cm from the detector's window and measured for a time period ranging from 24 to 72 hours, depending on their activity levels. Spectrum analysis was performed using GammaVision™

software, taking into account the respective natural background.



Figure 2. *The GEM80 detector and sample configuration*

Activity calculation

The activity at the end of the irradiation period, A_0 , was experimentally determined as following:

$$A_{0,\text{exp}} = \frac{C \times G_\gamma}{t_c \varepsilon_\gamma f_\gamma f_{\text{TCC}} e^{-\lambda t_d}}$$

where,

C are the Net counts registered during the counting time after dead time correction

t_c is the counting time

t_d is the time elapsed between the end of the irradiation and the start of the counting

λ is the decay constant for the product radionuclide

ε_γ is the Full Energy Peak Efficiency for the gamma-ray energy of interest

f_γ is the number of gammas per decay

G_γ is the self-attenuation correction factor

f_{TCC} is the true coincidence summing correction factor

Correction factors

Correction factors were applied on the spectrometry data to account for the effects of true-coincidence summing and self-attenuation of photons within the sample material. MCNP5 code [3] was employed to calculate the self-attenuation correction factor, G_γ , based on a detailed model of the counting geometry including the detector and sample, while TrueCoinc program [4] was used to produce true-coincidence summing correction factors for the cascade isotopes of interest.

RESULTS AND DISCUSSION

The results of the study, in terms of decay-corrected specific activities, are shown in Fig. 3a for a selection of samples representing all types of materials. It is noted that ^{60}Co was consistently detected in all samples, while ^{54}Mn was detected in 17 out of 21 samples. ^{46}Sc was identified only in Alloy 660 and Inconel samples. The analysis revealed the presence of ^{182}Ta , attributed probably to impurities induced in the fabrication processes of the materials, while ^{65}Zn was linked to brass depositions introduced during the material surface cutting techniques (EDM).

Moreover, the comparison of the results for the stainless steel materials studied (Figure 3b) showed comparable levels of specific activity for the main radionuclides detected. Higher activity values were observed for ^{57}Co and ^{58}Co , as compared to other isotopes.

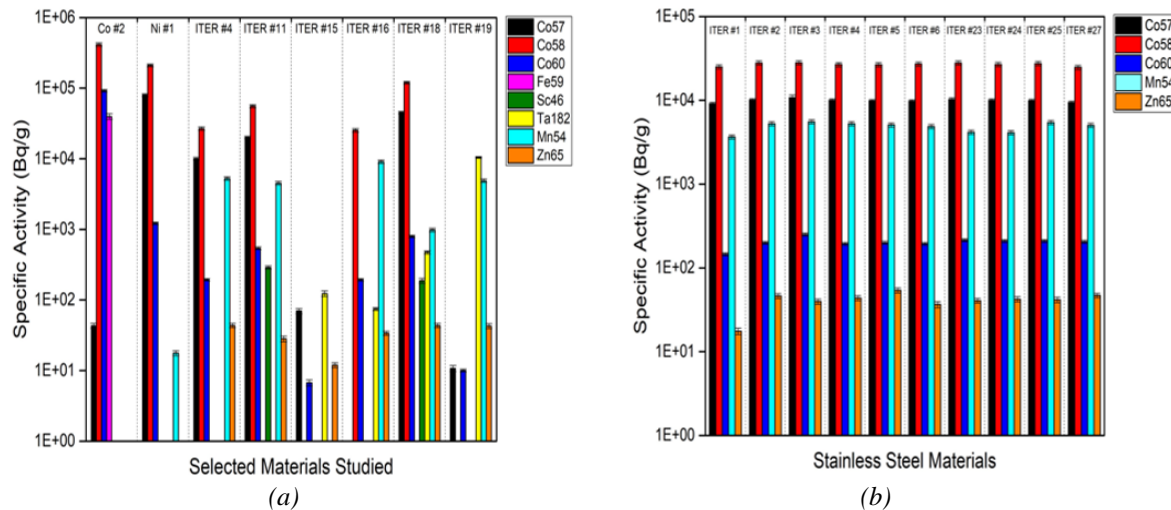


Figure 3. Decay-corrected specific activity of (a) selected materials (b) stainless steel materials

CONCLUSIONS

The findings of this study yield insight into the activation properties of materials used in ITER. The identification of impurities induced during material manufacturing procedures may enable targeted recommendations to manufacturers involved in ITER material production, regarding the material preparation and cutting methods. This work contributes to the ongoing endeavor of selecting materials that align with the operational demands and long-term sustainability goals of ITER.

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