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M. Scholz[1], S. Jednoróg[1], A. Murari[2], S. Popovichev[3], R. Prokopowicz[1],
A.SzydBowski[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*EURATOM - IPPLM Association, Warsaw, Poland*
[2]*Consorzio RFX Association EURATOM-ENEA,Corso Stati Uniti 35127 Padova, Italy*
[3]*EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK*
* See annex of F. Romanelli et al, "Overview of JET Results",
(Proc. 22 [nd] IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

1. INTRODUCTION

The fusion power generated by DD or DT plasmas in magnetic confinement devices is determined by measuring the total neutron yield. At JET, the primary diagnostic for measuring the time-resolved neutron emission is a set of fission chambers, whereas the timeintegrated neutron yield is measured by means of the activation technique [1]. The latter involves the irradiation of a sample of known mass by the neutron flux in specific locations close to the JET vacuum vessel. The induced radioactivity is then counted by a detector which is absolutely calibrated both in efficiency and energy. From the knowledge of the gamma emission probability, the half life, the detection efficiency and the timing of the irradiation, the total initial activity induced in the sample A0 can be determined. The initial activity is related to the total neutron yield Yn. The use of suitable (n,n'), (n,2n), (n,p), (n,α) nuclear reactions with different energy thresholds allows the measurement of both DD/DT yields and plasma neutron spectra [2]. Particularly for the evaluation of spectra, a novel kind of samples consisting of multi elements mixtures ("mixed sample") have been developed, prepared and deployed in JET.

The preliminary results of the measurements confirm the potential of the multielement activation technique for cross calibration of other neutron diagnostic systems and even rough neutron spectrum measurements.

2. SELECTION OF THE IRRADIATED ELEMENTS

First of all, we selected materials whose physical and chemical properties qualify them as suitable candidates for DD/DT neutron measurements. The chosen materials and the expected nuclear reactions are presented in Table 1 and Table 2 for DD and DT operation respectively . Some of the selected materials are not dosimetry standards and they have never been used to perform activation measurements, especially in fusion experiments.

3. EXPERIMENTAL SET-UP

The JET activation system is equipped with 8 irradiation ends [1]. Monte Carlo simulations have especially performed for so called 3-Upper irradiation end (3-U) – the only JET irradiation end placed inside the vacuum vessel [1]. Samples located in 3-U are exposed to relatively high neutron flux density and relatively low number of scattered neutrons in comparison to the seven other irradiation ends, which are located behind the tokamak shield. The samples located in the polyethylene capsule (JET standard) have been transported to and from the irradiation ends by the pneumatic system [3].

The γ-radiation emitted by the irradiated samples has been measured by a coaxial High Purity Germanium (HPGe) detector delivered by Canberra Inc.

4. EXPERIMENTAL RESULTS

All materials mentioned in Tables 1,2 have been tested in the last JET experimental campaigns.

Many of them appear to be very useful whereas some have been rejected. A number of reactions chosen for 2.5 MeV (Table 1) neutron measurements have been found very suitable for activation measurements. Particularly useful is yttrium which has not been used before as an activation sample.

Unfortunately, we had to abandon some of selected reactions. The products of reactions on bromine, zirconium, erbium and lead have too short half-live. They decay almost completely before they arrive to the detector. In case of gold, the gamma-lines emitted by the desired reaction product are overlaid by Compton background caused by the radiative capture reactions induced by scattered neutrons. In the case of selenium, cadmium and hafnium there are ambiguities in the original reaction in which the specific radio-nuclide is produced. The reactions induced in indium, yttrium and nickel appear to be very valuable. They have been detected with uncertainties less than 10%.

Among reactions singled out for 14MeV neutrons (Table 2) all reactions on aluminium, iron, cobalt, titanium and niobium have turned out to be useful. The induced activities are always low, nevertheless they have been usually estimated with uncertainties not larger than 10%–15%. During deuterium-tritium (or even during trace-tritium) operation at JET, the 14MeV neutron yield will increase by a ~two orders of magnitude. Then the uncertainties of measured activities will be much lower. The attempts to detect the isotopes from the reactions induced only by DT neutrons in zirconium, molybdenum, gold and lead have not been successful.

In addition to the classic solid activation samples, a novel kind of samples, consisting of multi-elements mixture ("mixed sample",) have been prepared and used at JET recently. They have been manufactured by pressing the powders of selected materials. These samples have measured several times after irradiation to detect successive decaying of induced nuclides. Such method permits to accelerate and simplify the acquisition of gamma-ray emitted from irradiated samples. It allows measuring short-lived nuclides because they all are measured at the same time. The composition of the multi-element samples has been selected to obtain a limited number of well-separated gamma-lines for which the number of counts under full energy peaks is approximately the same under similar irradiation and measuring conditions. The samples applied at JET are listed in Table 3. We found that a sample denoted as Mix12 in this table is particularly useful for fusion applications because it allows measuring low energy neutrons (scattered), 2.5 and 14MeV neutrons simultaneously. Measurements of specific activity for different isotopes from Mixed samples have been performed during the 2008-2009 JET experimental campaigns. The derived activity induced in yttrium right after the JET discharge as a function of the D-D neutron yield is presented in Fig.1. Fig.2 shows the similar diagram obtained for the samples sensitive to D-T neutrons (in particular for Mn-56 in the fig.2). Both pictures clearly indicate the good linearity between the calculated activity and the total or DT neutron emission obtained from fission chambers and the Si diodes.

CONCLUSIONS

For the evaluation of the neutron yield and spectra by the activation technique, up to twelve different elements have been irradiated in one JET discharge. A novel kind of samples consisting of multi-

elements mixtures ("mixed sample") have been developed, prepared and used in the last JET experimental campaigns. Specific activities for different isotopes have been obtained in one JET discharge. The comparison between those activities and the neutron yield measured by the JET neutron monitors has shown a good linear correlation. The results demonstrate the usefulness of the multi-element technique for the design of diagnostics for the next generation of large tokamaks such as ITER.

REFERENCES

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	Reaction	$T_{1/2}$		Reaction	$T_{1/2}$
1	Ti-47 (n,p) Sc-47	3.3d	1	Al-27 (n,p) Mg-27	9.5m
2	Fe-54 (n,p) Mn-54	312d	2	Al-27 (n,) Na-24	15h
3	Ni-58 (n,p) Co-58	71d	3	Ti-47 (n,p) Sc-47	84d
4	Se-77 (n,n') Se-77m	17s	4	Ti-48 (n,p) Sc-48	44h
5	Br-79 (n,n') Br-79m	5s	5	Fe-56 (n,p) Mn-56	2.6h
6	Sr-87 (n,n') Sr-87m	2.8h	6	Co-59 (n,) Mn-56	2.6h
7	Y-89 (n,n') Y-89m	15.7s	7	Co-59 (n,2n) Co-58	71d
8	Zr-90 (n,n') Zr-90m	0.8s	8	Zn-64 (n,2n) Zn-63	38.5m
9	Cd-111 (n,n') Cd-111m	49m	9	Zr-90 (n,p) Y-90	3.2h
10	In-115 (n,n') In-115m	4.5h	10	Zr-90 (n,2n) Zr-89	4.2m
11	Er-167 (n,n') Er-167m	2.2s	11	Nb-93 (n,2n) Nb-92	10.1d
12	Hf-177 (n,n') Hf-177m	51m	12	Mo-92 (n,2n) Mo-91	15.5m
13	Au-197 (n,n') Au-197m	7.7s	13	Au-197 (n,2n) Au-196	9.6h
14	Pb-207 (n,n') Pb-207m	0.8s	14	Pb-204 (n,n') Pb-204m	67m

Table 2:   *Table 2:*

Sample	Composition and mass fraction	Total mass (g)
Mix 5	Se (39.8%), Y (39.7%), Al (20.5%)	5.0511
Mix 6	Y (47.9%), Se (16.1%), Fe (15.0%), Si (20.0%)	4.8763
Mix 8	Y (47.2%), Se (15.9%), Al (16.0%), Fe (19.7%), Au (1.2%)	4.9643
Mix 9	Y (48.0%), Se (15.0%), Al (15.0%), Fe (20.0%)	4.9469
Mix 10	Y (50.0%), Se (16.7%), Al (16.7%), Fe (16.7%)	5.8976
Mix 11	Y (47.9%), Se (16.0%), Al (20.1%), Fe (16.0%)	4.9478
Mix 12	Y (40.0%), Al (30.0%), Fe (30.0%)	4.9973

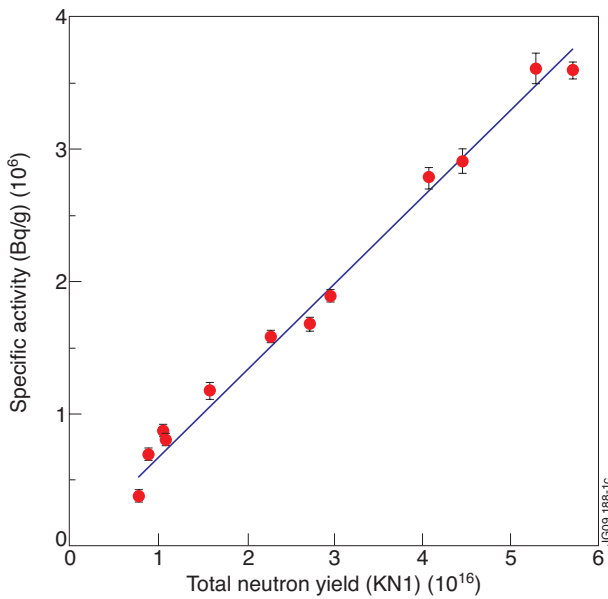*Table 3: The multi-element activation samples applied at JET*

Figure 1: Specific activity of Y-89m measured by means of HPGe detector vs total neutron yield.
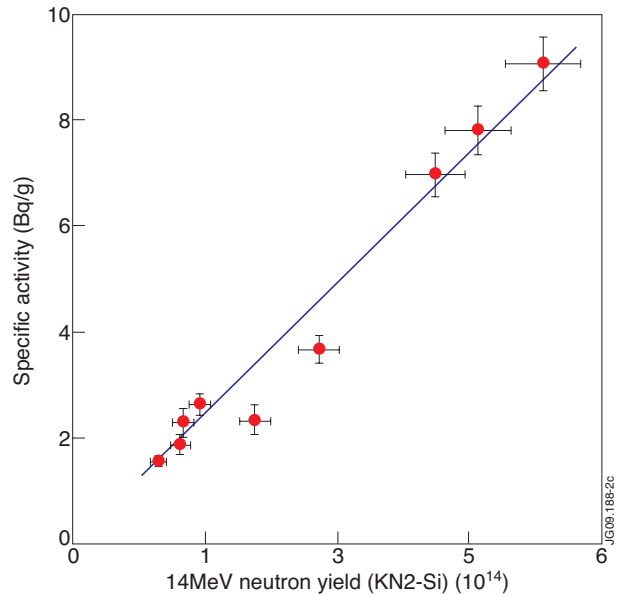

Figure 2: Specific activity of Mn-56 from cobalt sample versus 14MeV neutron yield.