Technological exploitation of the JET neutron environment: progress in ITER materials irradiation and nuclear analysis

L. W. Packer[a,1], P. Batistoni[b], N. Bekris[h], S. C. Bradnam[a], M. Fabbri[e], Z. Ghani[a], M. R. Gilbert[a], R. Kierepko[c], E. Laszynska[d], D. Leichtle[h], I. Lengar[f], S. Loreti[b], J. W. Mietelski[c], C. R.Nobs[a], M. Pillon[b], M. I. Savva[g], I. E. Stamatelatos[g], T. Vasilopoulou[g], A. Wojcik-Gargula[c], A. Zohar[f], and JET Contributors[2]

[a] CCFE, United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[b] ENEA - Department of Fusion and Technology for Nuclear Safety and Security via E. Fermi 45, 00044 Frascati (Rome), Italy
[c] Institute of Nuclear Physics, Polish Academy of Sciences, PL-31-342 Krakow, Poland
[d] Institute of Plasma Physics and Laser Microfusion, 01-497 Warsaw, Poland
[e] Fusion for Energy, Josep Pla 2, Torres Diagonal Litoral B3, 08019 Barcelona, Spain
[f] Reactor Physics Department, Jozef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[g] Institute of Nuclear and Radiological Sciences, Technology, Energy and Safety, NCSR Demokritos, Athens, 15310, Greece
[h] Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[1]Corresponding author
[2]See the author list of J. Mailloux et al. `Overview of JET results for optimising ITER operation', to be published in Nuclear Fusion: Overview and Summary Papers from the 28th IAEA Fusion Energy Conference

Introduction

The planned high profile DT experiments expected in the next few years at the Joint European Torus (JET) is expected to produce large neutron yields in the region of 10^{21} neutrons.

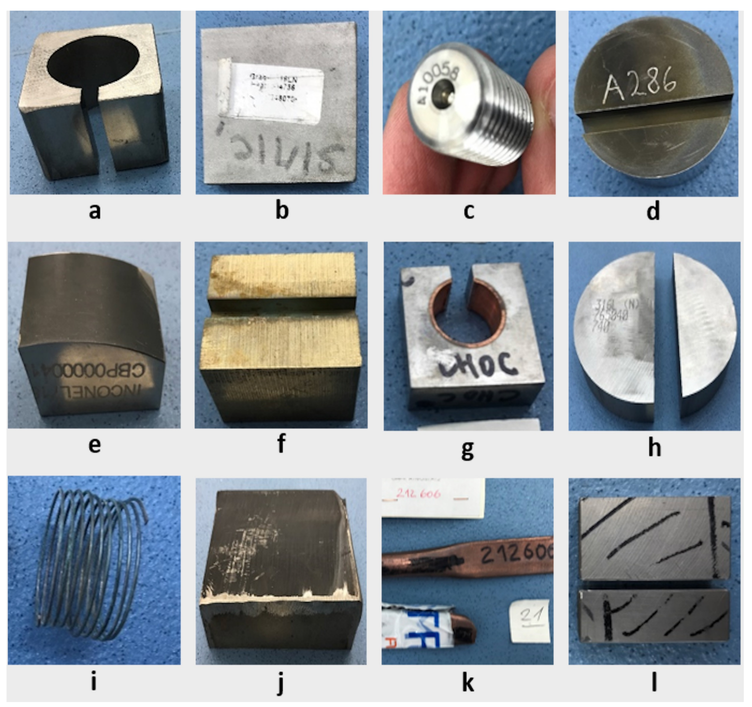
The scientific objectives of the experiments are linked with a technology programme, WPJET3, to deliver the maximum scientific and technological return through exploitation via the high neutron fluxes predicted at JET.

The 'ACT' subproject is focussed on the the irradiation of ITER materials within the JET neutron environment.

Motivation: Take advantage of the large 14 MeV neutron fluence expected during JET DTE2 to irradiate samples of real ITER materials used in the manufacturing of the main in-vessel tokamak components. -> Provision of benchmark data and improved understanding through measurement of nuclide activities for each material with comparison against the predicted quantities via calculation with neutron transport and activation codes and modern nuclear data libraries.

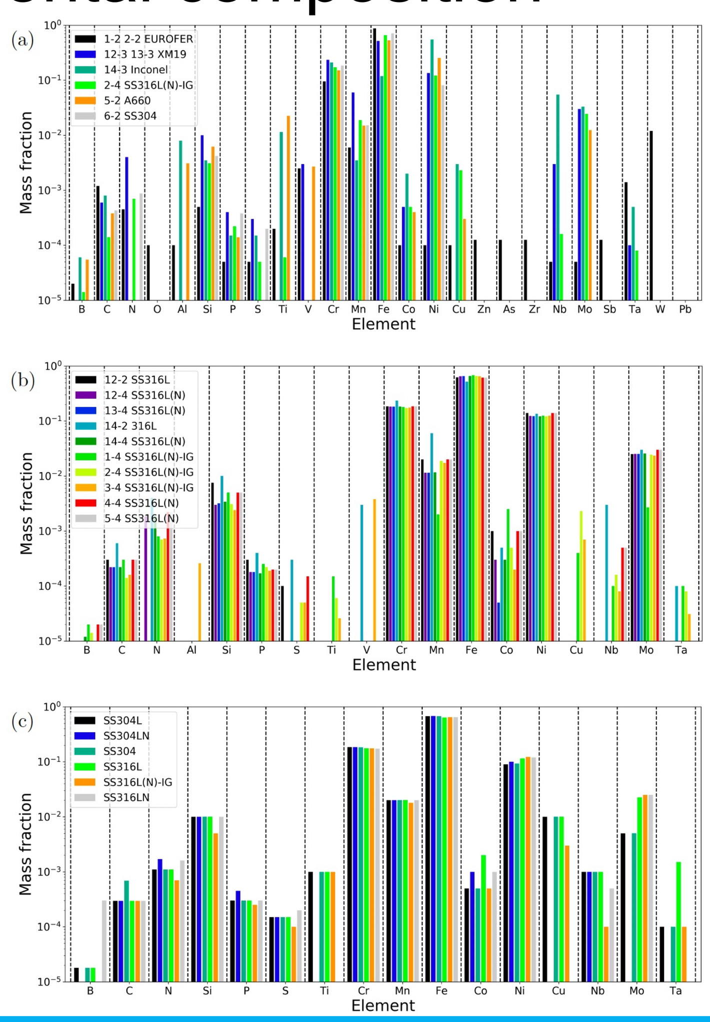
The status of the ACT subproject is presented here with particular focus on the analysis associated with the JET C38 D-D experimental campaign, where ITER materials with diagnostic foils have been exposed to the JET neutron environment for the first time, retrieved post-irradiation and then analysed by a number of participating laboratories.

ITER materials selected and elemental composition

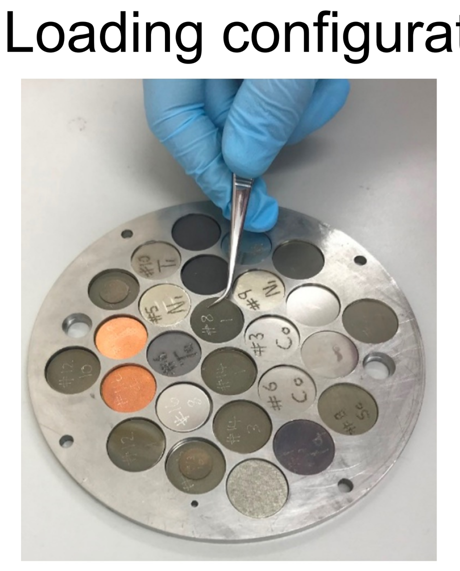


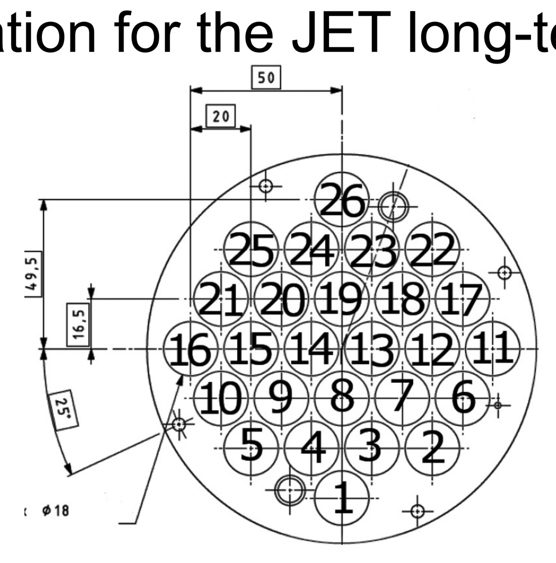
Selected ITER material bulk samples that were sourced by F4E: a) PF coil jacket; b) Radial closure plate for TF coil; c) TF coil case specimen; d) In-wall shielding material; e) Inconel 718; f) Divertor material g) Divertor W monoblock; h); Vacuum vessel forging; i) Reacted TF strand; j) Vacuum vessel plate; k) CuCrZr pipes for the divertor; l) Eurofer 97-2 material.

RHS plots: (a) Comparison of the elemental composition of various ITER steels as defined by the associated certificates. LTIS position IDs are provided in the legend and may be used with the table shown in the box below for fuller details; (b) 316L alloy steels from different manufacturers (or batches) as defined in the associated certificates; (c) various steels as defined within the ITER materials activation handbook.



Loading configuration for the JET long-term irradiation station (LTIS)

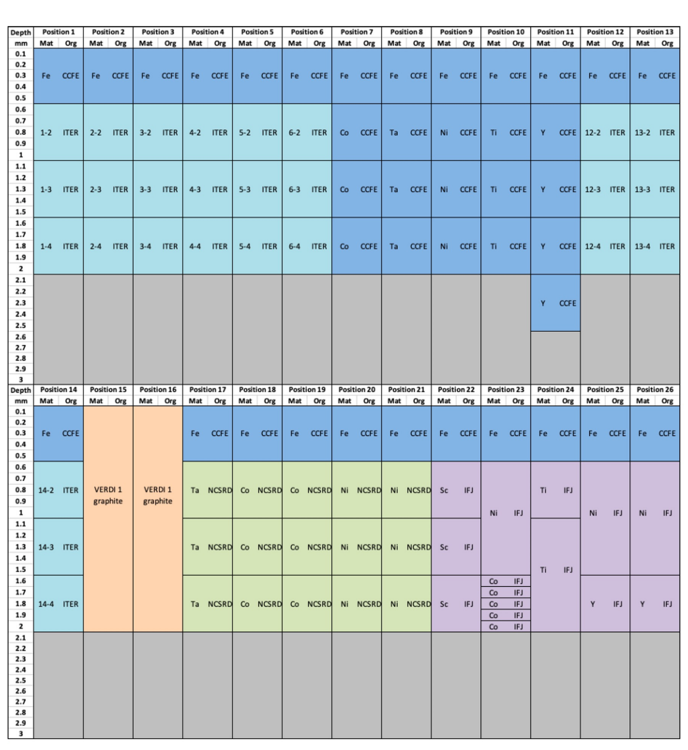




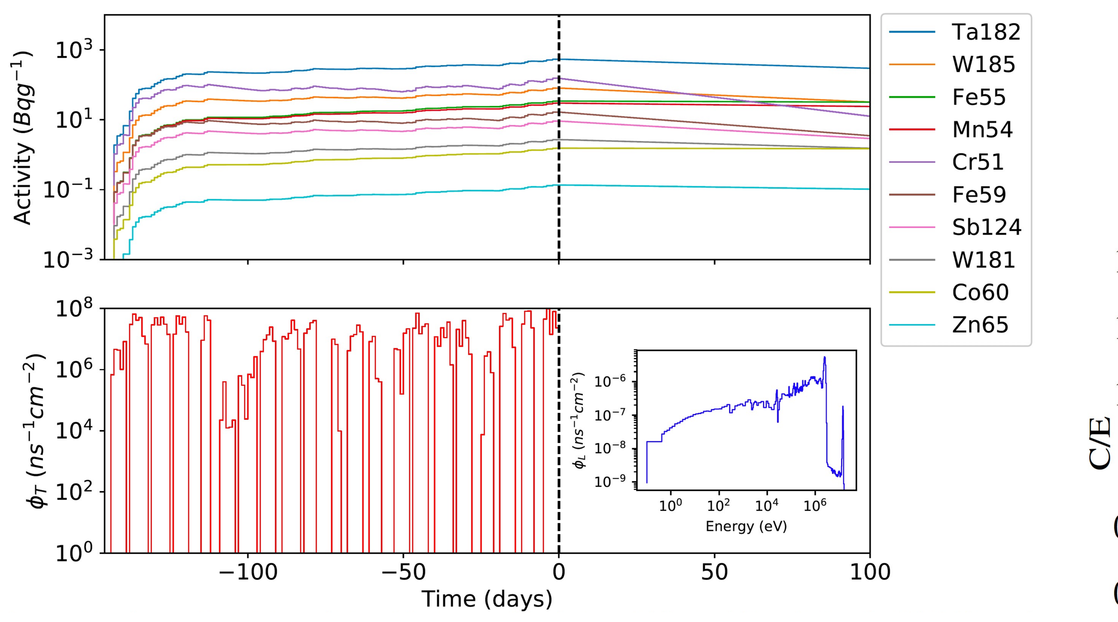
Long term irradiation station sample assembly dosimetry foil and ITER material sample arrangement by sample cavity position numbers, 1-26

Table below: ITER material description, unique LTIS position ID and other relevant details for irradiated samples exposed during the JET C38 irradiation campaign. The sample LTIS position-depth ID may be used to map to the LTIS configuration shown in the RHS figure below. The ITER materials are shown as light blue boxes with a corresponding unique position--depth identifier, which may be matched with the table to provides the full ITER material description. Other colours shown denote the institute laboratory responsible for post-irradiation analysis of various dosimetry foils.

Sample LTIS position–depth ID	Material	Manufacturer and sample details	Analysis Laboratory	Sample batch ID	Measured sample mass (g)	Nominal thickness (mm)	Nominal diameter (mm)	Nominal density (g/cm^3)
1-2	EUROFER	Saarschmiede Gmbh Vacuum Induction Melting (VIM) + Vacuum Arc Remelting (VAR) 1.4914x3 EUROFER 97-2, order no: 8186097	CCFE (UK)	6a_8	0.356	0.5	11	7.87
3-2	Al–Bronze	Aubert & Duval, used for the ITER inner vertical target (IVT), Copper Alloys Ltd. Cast ID: 51519051		9_2	0.857	0.5	17.5	7.6
5-3	Tungsten	AT&M for ATMOSTAT, W monoblocks, purity 99.5, ref: PD-13482-999		13_1	0.705	0.5	10	19.3
5-2	A660 alloy	Carpenter powder products, India DA, ITER In Wall Shield (IWS), Heat Nr 5600413		10a_10	0.886	0.5	17.5	7.92
6-4	316L(N)	Thyssen Krupp Materials France SAS, Radial plates for the ITER toroidal field coils, 316LN Class C2 solution treated and quenched, stress relieved (2500/33)		4c_9	0.506	0.5	13	7.93
12-4	316L(N)	Special TF cover plate (304757)		3a_1	0.927	0.5	17.5	7.93
12-3	XM19	Aubert & Duval, Forgings for divertor cassette		14_3	0.921	0.5	17.5	7.88
12-2	316L	Salzgitter Mannesmann Stainless Tubes GmbH, Poloidal field coil jacket		2_10	0.886	0.5	17.5	7.93
14-3	Inconel	Inconel alloy 718		8_1	0.967	0.5	17.5	8.2
14-2	316L	Divertor Nadege 316L		15_3	0.92	0.5	17.5	7.93
3-4	316L(N)-IG	Thyssen Krupp Materials France SAS, forged block ITER grade vacuum vessel plate, specimen number 5939		5b_1	0.925	0.5	17.5	7.93
3-3	CuCrZr	Yamato, First wall component, Divertor pipe 212601		11b_4	0.953	0.5	17.5	8.9
2-3	A660 alloy	ITER divertor material		12_1	0.925	0.5	17.5	7.92
1-4	316L(N)-IG	Industeel Groupe Arcelor, ITER vacuum vessel plate	ENEA (Italy)	5a_9	0.9258	0.5	17.5	7.93
4-4	316L(N)	Thyssen Krupp Materials France SAS, Radial plates (jacket) for the ITER toroidal field coils (2500/64)		4a_9	0.8795	0.5	17.5	7.93
14-4	316L(N)	Special TF cover plate (304756)		3c_1	0.9258	0.5	17.5	7.93
1-3	A660 alloy	ITER divertor material		12_10	0.924	0.5	17.5	7.92
6-3	Tungsten	AT&M for ATMOSTAT, W monoblocks, purity 99.5, ref: PD-13482-999		13_10	tba	0.5	10	19.3
13-3	XM-19	Aubert & Duval, Forgings for the ITER divertor cassette		14_1	0.9104	0.5	17.5	7.88
2-2	EUROFER	Saarschmiede GmbH, Vacuum Induction Melting (VIM) + Vacuum Arc Remelting (VAR) 1.4914x3, EUROFER 97-2, order no: 8186097		6b_1	0.5023	0.5	11	7.87
6-2	SS304	Carpenter powder products, India DA, In wall shield sample (IWS)		10b_2	0.9236	0.5	17.5	7.85
13-2	A286 alloy	Villares Metals, ITER In wall shield (IWS)	IFJ/IPPLM (Poland)	7_1	0.9172	0.5	17.5	7.92
4-3	CuCrZr	KME, First wall component, divertor pipe 212606		11a_1	1.0018	0.5	17.5	7.93
13-4	316L(N)	Special TF cover plate (304761)		3b_1	0.9381	0.5	17.5	7.93
4-2	Al-Bronze	Aubert & Duval Copper Alloys Ltd. For the inner vertical target (IVT), Cast ID: 51519051	NCSRD (Greece)	9_3	0.85251	0.5	17.5	7.45
5-4	316L(N)	Thyssen Krupp Materials France SAS, Radial plates for the ITER toroidal field coils, 316LN Class C2 solution treated and quenched, stress relieved (2500/68)		4b_10	0.88502	0.5	17.5	7.93
2-4	316L(N)-IG	R Kind GmBh, ITER vacuum vessel plate		5c_9	0.92449	0.5	17.5	7.93

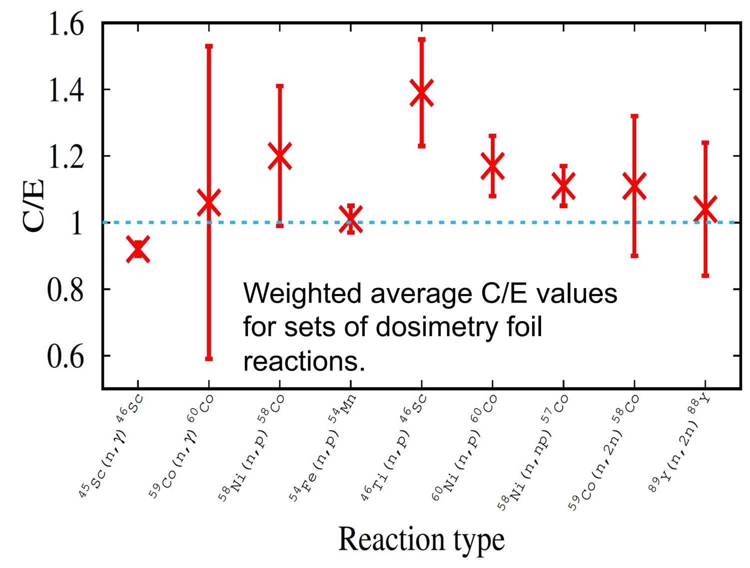


Activation predictions and experimental validation using dosimetry foils

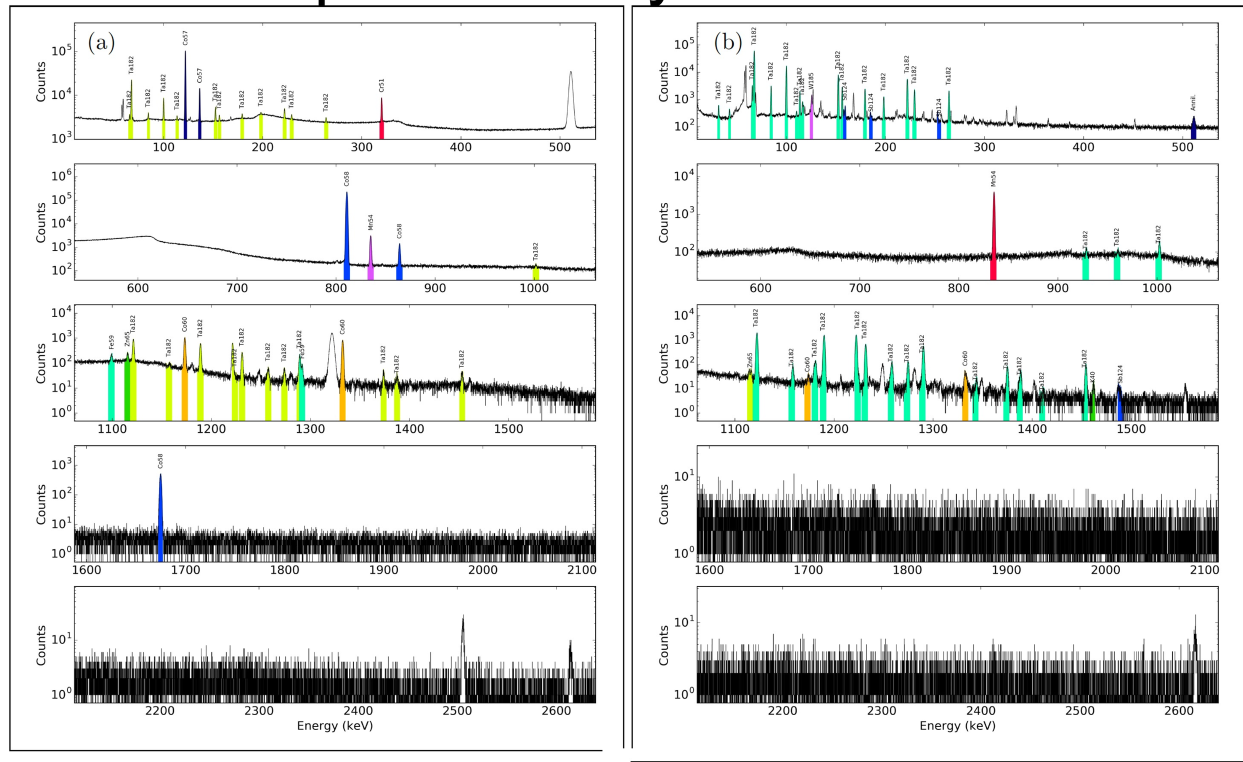


Top plot: specific activity prediction of dominant nuclides during and following JET irradiation of a EUROFER sample. The dashed vertical line denotes the time at which the samples were removed from the JET LTIS. Bottom plot: daily neutron fluence averaged over the sample volume within the LTIS. The inset plot shows the neutron energy spectrum averaged over the sample volume within the LTIS.

Experimental validation of neutron transport and activation simulations

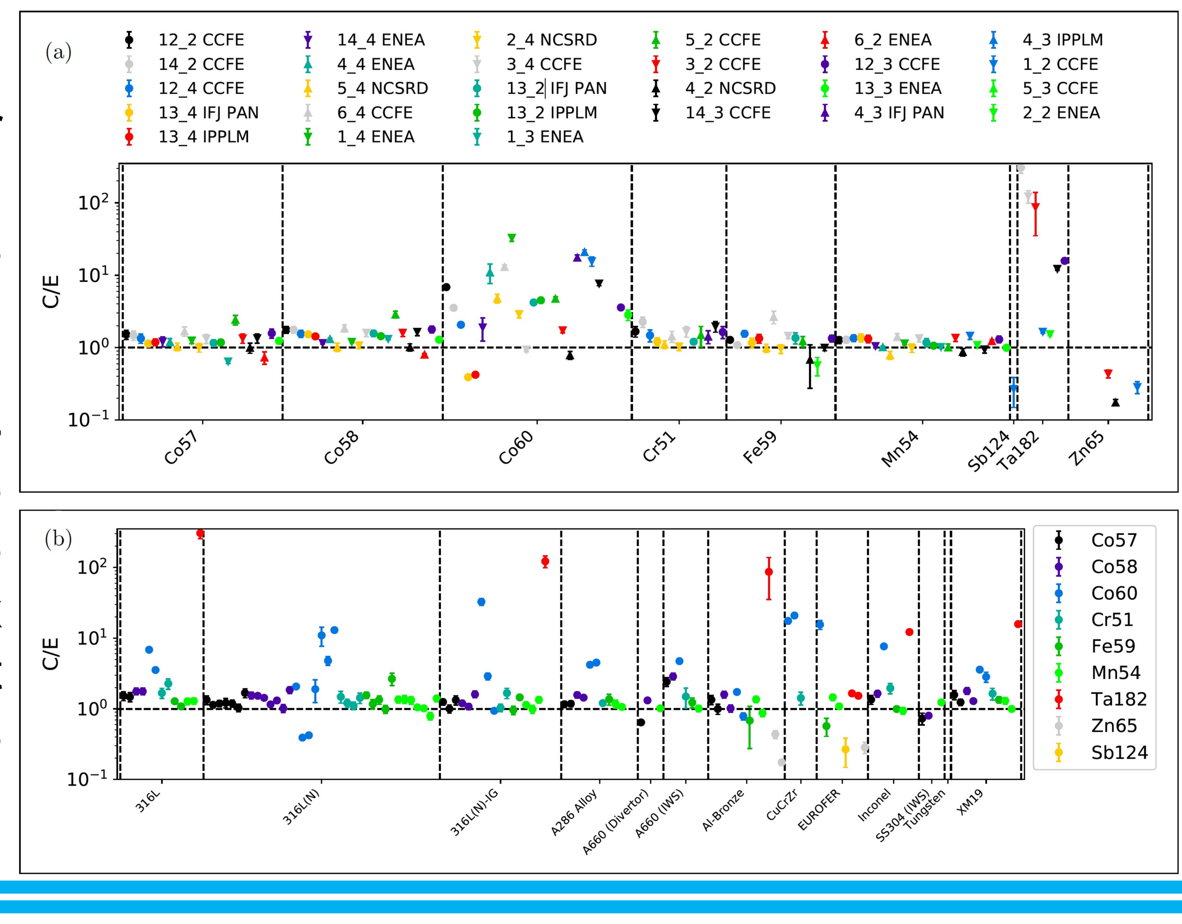


Gamma spectrometry and C/E results



LHS plots: High resolution gamma spectrometry measurements using a HPGe instrument for: (a) Inconel sample position ID: 14-3; (b) EUROFER-97 sample position ID: 1-2

RHS plot: C/E values for measured and calculated ITER materials: (a) results grouped by measured isotope. The legend indicates the position-depth ID linked to the material description in the table in the bottom left box and the measurement laboratory; (b) results grouped by material type.



Conclusions

27 ITER material samples were exposed to neutrons from the JET plasma with a neutron yield of 3.151E19. The samples were then retrieved and distributed to a number of participating laboratories. The analysis identified a number of activation products present in each sample and corresponding modelling predictions have been compared against these observations.

The dosimetry foil measurements for 9 reactions generally show that the calculated neutron fluence for the fast neutron spectrum, including the D-T fraction due to triton burn-up, and the thermal neutron region is close to the experimental observations, though may be revised in future analyses. For the ITER material results the full data set of C/E values per measured isotope has been presented briefly with some initial remarks in this short paper, though will be discussed in more detail in a more extensive future paper. The measurements for ^{54}Mn, ^{58}Co and ^{57}Co are observed to be close to 1 and a relatively greater spread in C/E results for ^{60}Co and ^{59}Fe results is evident. Highlighted discrepancies in C/E values have been noted for ^{65}Zn, ^{124}Sb, and ^{182}Ta.

Preparations for future activities: Installation of the LTIS with new samples was completed in September 2020, in readiness for the combined irradiation of the LTIS during the C40 T-T experimental campaign in 2021 followed by the DTE2 (D-T) campaign. The samples included a range of ITER materials, dosimetry foils, VERDI detectors and thin samples of W, Mo and Fe to study for radiation-induced defects. These samples are expected to be retrieved following and then measured either by low background HPGe gamma spectrometry techniques or, in the case of the thin W, Mo and Fe samples, measured by the Positron-Annihilation Lifetime Spectroscopy (PALS) technique to determine the density and size distribution of radiation-induced defects.

'This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.