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Fusion Technology Activities at JET: Latest Results

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** See annex of F. Romanelli et al, “Overview of JET Results”,*
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ABSTRACT

The JET Task Force Fusion Technology (TF-FT) was launched in 2000 to use the unique capabilities, facilities and operating experience at JET to provide significant contributions to the research programme on both JET and ITER. This paper presents the most recent results obtained within the JET TF- FT programme.

The Tritium (T) retention measurements have confirmed high surface but little bulk T concentrations on the MKII-SRP divertor tiles while T thermal desorption tests confirmed the necessity to reach at least 600 °C. From the 2007 shutdown the MKII-HD (more ITER like) divertor has revealed some slight changes in the nature of the erosion/deposition. In order to improve analysis, time resolution devices such as quartz micro-balances and rotating collectors have been located beneath the divertor for deposition and plasma physics correlations. Due to improvement of dedicated models and technologies, in situ laser techniques for detritiation and characterisation/ removal have provided encouraging results on quantitative characteristics (composition, thickness, adherence, temperature) of deposited films on plasma facing components. A particular effort on temperature control of the new metallic ITER-Like Wall (ILW) that is presently being installed in JET has been pursued with active laser infrared thermography. JET TF-FT also contributes to the operator strategy to comply with the safety agency requirements for T management. Recent results on two major topics - purification of tritiated water and development of the ^{3}He method for the determination of the T concentration in waste drums - are presented. Finally, this paper also presents some activities in preparation of the ILW for the pre-characterization of marker tiles and the refurbishment of diagnostics for deposition characterization.

1. INTRODUCTION

Tritium management is one of the main technological challenges for future tokamak operation on route to industrial development. For this purpose, studies of the physics of T implantation and desorption from Plasma Facing Components (PFCs), T mapping inside the vessel, the forms in which T is trapped and how it could be removed from the vessel, T storage and recycling as fuel, have been and continue to be performed on various fusion machines.

Since 2000 the JET TF-FT aims at contributing to this challenge by launching experiments and analyses to be performed at JET, in collaboration with Euratom Associations, on T retention, material transport and erosion/deposition, detritiation/removal techniques, and on T management. [1-5]. JET TF-FT includes also other activities in the fields of neutronics, safety and engineering. This paper presents the latest results with focus on the measurements of the in-vessel spatial location of hydrogen isotopes as well as on the development of techniques to characterize, remove and manage the T inside and outside the vessel.

2. TRITIUM RETENTION

The study of the spatial distribution of hydrogen isotopes inside the JET carbon plasma facing components is always of paramount importance for T management. Two campaigns with T have been performed on JET since the installation of the divertor: in 1997 (99.5g in total with recycling) and in 2003 (5.4g in total). Although 90% of the T remaining inside JET has been found in flakes below the divertor structure due to erosion and re-deposition of carbon layers [6,7], depth profiles of T trapped in the bulk tiles and the release of T by thermal desorption have been investigated . As re-deposition of carbon is mainly concentrated in the inner part of the divertor, two Tile 4 from different toroidal locations named 3BWG4A and 14BWG4B from the MKII-SRP divertor (which was in use from 2001 to 2004) have been analysed. The results of depth profile measurement show for both tiles that 99.9% of the total T activity is located in the first 1 mm slice (A1 disk) with very little diffusion into the bulk. They also confirm previous surface measurements done on the same tiles [8-9].

Tritium release by thermal desorption has also been performed for the A1 disks from several cylinders cut from the inner part (n^o 1) to the louvres (n^o 11). Figure 1 shows the time evolution of the release rates and the temperature of desorption. It is worth noting that the release rate is much higher (30 times for cylinder 4) and begins at lower temperature (150 deg.C) compared to previous and similar studies [10] made on MKI divertor tiles (release starting at 600 deg.C). A possible reason is the presence of co-deposited layers on the surface of A1 disks from the MKII divertor as the MKI divertor tiles had comparatively clean surfaces before treatment.

3. MATERIAL TRANSPORT AND EROSION/DEPOSITION

Since JET has been converted to divertor configuration in 1993, five different divertor designs have been tested including the “Gas box” divertor concept called MkII-GB from 1998 to 2001 which sought to demonstrate the effect of a septum between inner and outer divertor legs as will be used in ITER. However, an important parameter for ITER is the triangularity of the plasma, so in 2004 JET installed the MII-HD (high delta) divertor to explore this parameter and it is still in use at the present time (Fig. 2). In the high triangularity mode the outer strike point is on the load bearing tile and the inner strike point is either at the top of tile 3 or on the lower part of tile 1. The more symmetrical configurations used with previous divertors are also used for comparison. The general pattern of erosion/deposition has been found very non-uniform in all divertor designs, with mainly heavy deposition in the inner divertor, whilst most of the outer divertor exhibits net erosion.

However, careful comparison of tiles removed in the last three shutdowns (2001, 2004 and 2007) shows a progressive change in the nature of the deposition at the outer divertor corner. Increasing deposition at the outer shadowed region and louvers are observed and increasing Be/C ratios on the sloping part of tile 6; there is also an increase in Be/C ratios on the sloping part of tile 4 (though values are lower than for tile 6).

Post mortem analyses of tiles provide information on erosion/deposition resulting from exposure during all operations whilst the tiles were in the machine. In order to differentiate the erosion/deposition patterns, time resolution devices such as Quartz MicroBalances (QMB) and Rotating

Collectors (RC) have been implemented in shadowed corners of the divertor. QMBs measure the erosion/deposition on a shot-by-shot basis [11], whereas the resolution of the RC is about 30-60 pulses depending on width of the entrance slit [12]. However, the RC gives a quantitative measurement of the deposition whereas the QMB data are qualitative as demonstrated for deposition under the load-bearing tile in ref.12. Figure 3 shows the time-resolved deposition measured on the RC and the QMB frequency (which is proportional to the integrated weight of deposit) as a function of pulse number – the RC stops rotating after ~3000 pulses (pulse ~67500), so deposit from all subsequent pulses accumulates in the peak at that point. Both the RC and QMB were located in the outer divertor.

There is a reasonable correlation in the periods of most deposition between RC and QMB, however it is proving difficult to correlate with the nature of the JET pulses (no direct correlation apparent between peaks in deposition and the position of the outer strike point). Work is continuing to relate RC data to plasma density and temperature.

4. IN-SITU TECHNIQUES FOR DETRITIATION AND CHARACTERISATION/ REMOVAL

As the first ITER divertor will probably include carbon tiles at the highest loaded target section, they might be sensitive to sputtering and T sorption. The consequent erosion/deposition could lead to highly tritiated co-deposit layers as observed inside JET. This monitoring is probably the most challenging due to the complexity of implementing control techniques. Indeed, to detritiate in-situ one first needs to i) characterize, secondly to ii) remove the T content and finally to iii) transport the products outside the vessel.

The two first steps are currently studied within the JET Fusion Technology program:

i) The characterization of layer surfaces concerns both surface temperature by active infra-red thermography and assessment of the thermal properties by a lock-in thermography method. The active thermography aims at preventing reflective flux in a metallic environment, and has recently proved its ability to measure surface temperature up to a distance of 2.15 meter between the sample and the detector. Results on ITER-like wall samples (W+4mm C) are very encouraging. Compared to the model, the maximum relative error DT/T is (at T=728 K) of 3.4% (DT=25 K). In a highly reflective environment with stainless steel samples, the maximum relative error DT/T found (at T=785 K) was 4.8% (DT=38 K). The next steps will be the improvement of the signal quality and the device modification to be JET compatible (e.g. measuring from a distance of 7 m which is a typical viewing port to in-vessel wall distance).

The lock-in laser thermography [13] method (1064 nm, 100 ns, 1-10 kHz, 200 W) using repetitive heating (10-100 Hz and duration 1-100 ms) aims at providing quantitative data on the layer (thickness and composition) and on the interface to the substrate (layer adhesion). For layer thickness and composition, studies concern the thermal model validation on several samples: Graphite-Al/C+H (Al is used as a Be substitute), AISI304-W-DLC+H and IG11-W-DLC+H. The laser phase-shift response curve for the samples is fitted to the model for which the substrate and layer characteristics have been manually fitted. For layer adhesion, the method relies on a theoretical model of the phase shift dependence on the laser repetition rate (Hz) and the heat transfer coefficient between the layer and the substrate. Figure 4 shows results from two different cases of layer adhesion for a 140 µm W on a CFC substrate.

ii) For removal of highly tritiated deposited carbon layers, the efficiency of many techniques has been assessed on JET samples [14]. Laser cleaning by ablation appears to be the most promising technique by removing carbon-based deposits at high rates > 10-2 g/s, and also allows detritiation of gaps and castellations. The method uses ablation threshold adjustment between the layer and the substrate in order to avoid damage of the substrate (fluence up to 12 J/cm2). This ablation threshold is related to a thermal model which is under development for layer properties that can be determined from fitting of the experimental/simulated results. The model validation has mainly concerned carbon-based deposits [15] but recent ablation tests on several ITER-like wall samples with fitted laser fluence thresholds have started.

iii) For transport of dust produced by ablation, no significant studies have been made in this work.

The Laser Induced Breakdown Spectroscopy (LIBS) device intends to merge the above three steps into a single device. It aims at providing non-intrusive and quantitative information on the composition of a surface [16]. Qualitative results have been obtained by the past from preliminary tests on TEXTOR tiles and even using the edge LIDAR on JET [17-18].. Analytical spectral lines (Hα, C+, Cr, Be, W) evolution versus laser shots number has been observed from the laser produced plasma. Recently and within the JET TF-FT a first attempt of quantitative measurement has been tested with calibrated samples. Figure 5 shows results of integrated carbon lines from spectra obtained from two different mixed C/W/O samples (C 70%, W 27%, O 3% ; C 82%, W 15%, O 3%).

The spread in the results from the second sample could be due to sample preparation and needs to be confirmed. In the future similar analyses will be done on calibrated amounts of hydrogen and deuterium in mixed C/W layers. It is hoped that a successful LIBS diagnostic will emerge provided that a large calibration database on real samples (with wide spectrum of mixed Be/W/C) can be realized and further efforts are made on the development of a model for spectrum prediction. The edge LIDAR laser at JET has been maintained in place for possible future validation on real samples during operation with the ITER-like wall.

5. TRITIUM MANAGEMENT

A detritiation studies programme is carried out at JET-Culham site with the primary aim of identifying processes which could potentially reduce the level of contamination in waste to below the 12GBq/tonne threshold for Intermediate Level Waste (ILW) to permit the disposal as Low Level Waste (LLW).

Because tritiated water is the main product from various detritiation processes, a significant effort, for either the current strategy (sending back to Canada) or the long term strategy (building a process for on-site treatment) is devoted to the water purification before its decontamination. For that purpose an installation has been studied based on ion exchange columns preceded by an active carbon bed and followed by a microporous filtration cartridge and a final filter.

The installation has operated for an average JET grade of tritiated water and a grade close to the expected maximum T content. The capacity of the installation is 6 liter/h, which is a one tenth-scale version of what would be required for the total treatment of JET tritiated water in 100 working days. For both grades, the installation [19] has reached the current requirement of purity level (conductivity $\sigma < 5$ mS/m and chemical species concentrations). The total waste stream from this installation scale is about 2.6 kg/m^3 of treated water.

Determination of the T concentration in waste drums by non-intrusive/destructive methods is highly desirable for waste management (inventory for safety, transport and storage). The assessment of the ^{3}He method has been launched in 2006 by measuring the equilibrated ^{3}He drum leak (proportional to T activity due to radioactive decay) collected in an external tight confinement chamber (70 litre) around the 200 litre drum [20]. Representative soft housekeeping (0.2 TBq measured by scintillation) and metallic waste (8.6 TBq measured by calorimetry) from JET have been inserted in 3 separate drums. For housekeeping waste the method is applicable as the equilibrium state obtained after 5 months is in good agreement (+/- 25 %) with the reference activity. It is worth noting that the equilibrium could have been achieved in a shorter time if the drum were not sealed as airtight as it was.

For metallic waste drums, the unexpected results (no equilibrium reached) throw doubt on the applicability of the ^{3}He method. Possible explanations concern the initial high T outgassing due to high activity and/or retention of T and ^{3}He around microstructural defects in metal matrix. Results suggest that the most suitable T measurement methods both in the case of JET and of ITER are as shown in Table I.

This table shows that the ^{3}He method can be applied for most of the housekeeping produced by JET or ITER fusion reactors, excepted for low activity waste from JET, whilst for metallic waste (1st barrier and other types of waste) alternative methods should be employed. Nevertheless, once a detritiation treatment has been applied, the ^{3}He method might be applicable to some metallic waste depending on the detritiation factor.

6. EROSION/DEPOSITION DIAGNOSTICS FOR THE ITER-LIKE WALL (ILW)

All the plasma-facing tiles in JET that were previously C-based are being replaced, generally with either solid beryllium (Be) or Be-coated Inconel in the main chamber and solid tungsten (W) or

W-coated CFC tiles in the divertor. Thus material transport and H-isotope retention can be measured with the same wall materials as planned for the active phase of ITER. Special marker tiles have been developed to measure the erosion/deposition and compare with the previous C-wall and are being installed at selected sites throughout the vessel. The marker tiles at sites with solid Be tiles have an interface layer of nickel and a top coating of ~8 microns Be on the Be substrate. The tiles have been accurately profiled to see if erosion >10 microns occurs; ion beam analysis before and after use will show erosion of <8 microns, or any net deposition. Marker tiles have also been prepared for the W-coated divertor, which in this case have a molybdenum interlayer and a W top layer of ~4 microns.

New QMBs and RC units are fitted at the same sites as for previous campaigns, to give direct comparisons. Transport of impurities is expected to the shadowed regions at the divertor corners and the amount of H-isotope retention will be significantly reduced.

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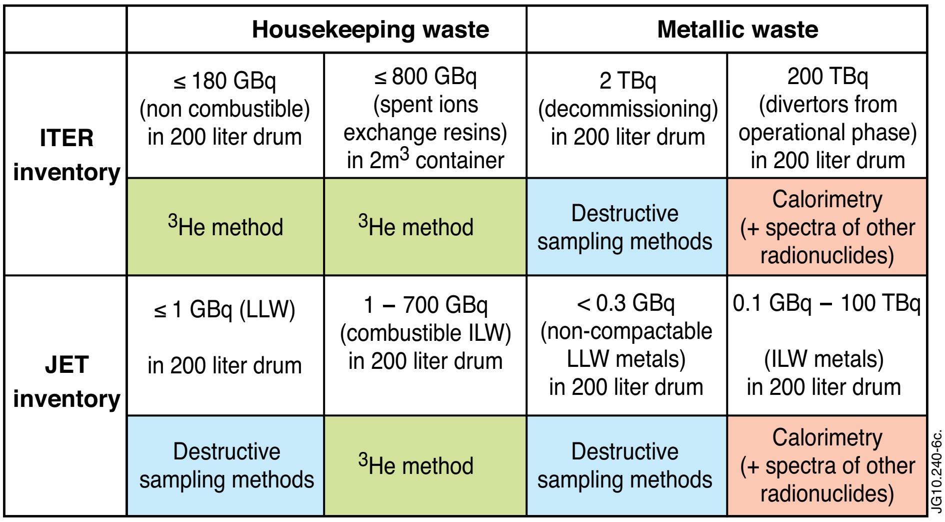

	Housekeeping waste		**Metallic waste**	
ITER inventory	≤ 180 GBq (non combustible) in 200 liter drum	≤ 800 GBq (spent ions exchange resins) in 2m^3 container	2 TBq (decommissioning) in 200 liter drum	200 TBq (divertors from operational phase) in 200 liter drum
	^{3}He method	^{3}He method	Destructive sampling methods	Calorimetry (+ spectra of other radionuclides)
JET inventory	≤ 1 GBq (LLW) in 200 liter drum	1 – 700 GBq (combustible ILW) in 200 liter drum	< 0.3 GBq (non-compactable LLW metals) in 200 liter drum	0.1 GBq – 100 TBq (ILW metals) in 200 liter drum
	Destructive sampling methods	^{3}He method	Destructive sampling methods	Calorimetry (+ spectra of other radionuclides)

Table I: Selection of suitable T measurement methods for ITER and JET specific types of waste.

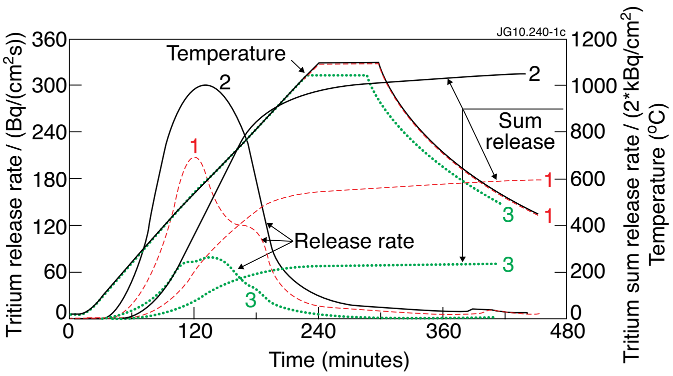

Figure 1: T release by thermal desorption from the A1 disks of cylinders 1 (1), 4 (2) and 5 (3) of the Tile 4 numbered 14BWG4B. The location of Tile 4 is as shown in Fig.2, although this is a later divertor.

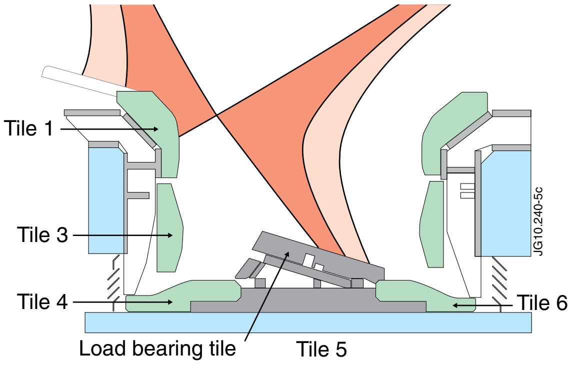

Figure 2: Cross-section of the JET MII-HD divertor installed in 2004 and still in use.

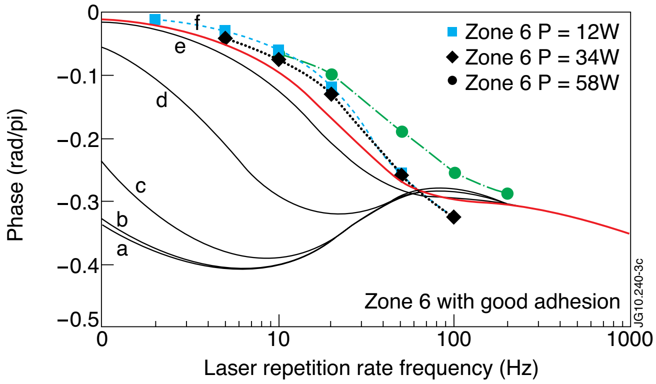

Figure 3: C and D concentration (left-hand scale) on the outer divertor RC compared with QMB signal in Hz (proportional to weight of deposit – right-hand scale).

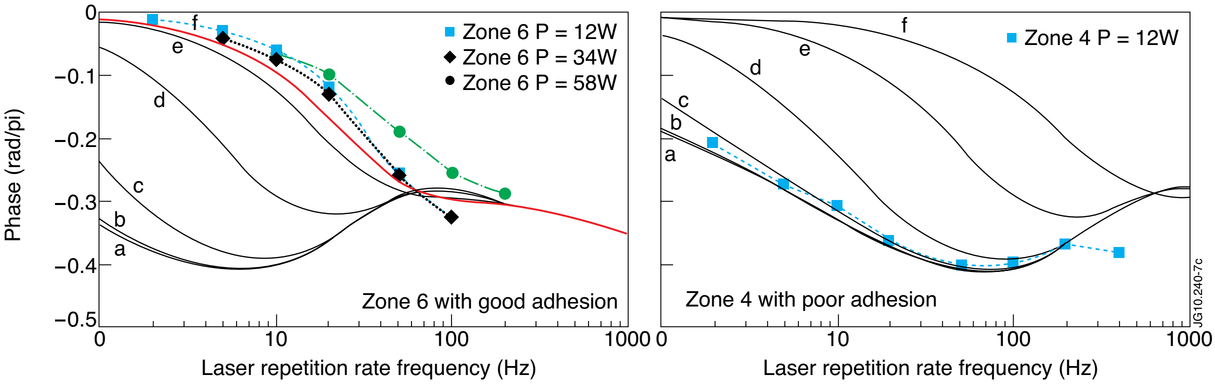

Figure 4: Layer adhesion characterization for good adhesion (left) and poor adhesion (right).

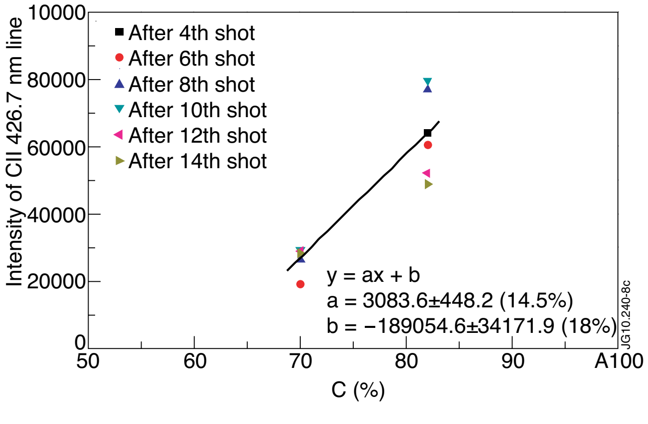

Figure 5: Calibration curve for carbon ratio in the mixed material samples.