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S. Ciattaglia[1], B. Benoit[2], P. Coad[3], A. Coletti[4], O. David[5], R.A. Forrest[3], E. Gauthier[6], C. Grisolia[6], R. Lässer[7], J. Likonen[8], M.J. Loughlin[3], M. Mayer[9], L. Nicolas[10], T. Pinna[4], F. Scaffidi-Argentina[1], S. Shaw[3]
and contributors to the EFDA–JET workprogramme*

[1] *EFDA Close Support Unit, Culham Science Centre, Abingdon OX14 3DB, UK*
[2] *Association Euratom/SCK-CEN, Boeretang 200, 2400 Mol, Belgium*
[3] *Association Euratom/UKAEA, Culham Science Centre, Abingdon OX14 3DB, UK*
[4] *Association Euratom-ENEA sulla Fusione, C.R.Frascati, via E.Fermi, 45, C.P. 65, 00044 Rome, Italy*
[5] *Association Euratom/CEA, Centre de Cadarache, F-13108 Saint Paul Lez Durance, France*
[6] *Association Euratom/CEA/Fontenay-Aux-RosesBP6, 92265, CEDEX, France*
[7] *Association Euratom/Forschungszentrum Karlsruhe, Postfach 3640, 76021 Karlsruhe, Germany*
[8] *Association Euratom/TEKES, VTT Chemical Technology, P.O. Box 1404, FIN-02044 VTT, Finland*
[9] *Association Euratom/IPP, Max-Planck-Institut für Plasmaphysik, Boltzmanstr. 2, 85748 Garching, Germany*
[10] *Association Euratom/CEA Saclay - Bâtiment 607, DEN/DM2S/91191 GIF-SUR-YVETTE, France*
[*] *See annex of J. Pamela et al, 'Overview of Recent JET Results and Future Perspectives', Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

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ABSTRACT.
Research activities that provide contributions or solutions to important technological issues for both JET and ITER are carried out within the Fusion Technology (FT) Task force (TF) at JET and in the European national laboratories in collaboration with the JET Operator (UKAEA). They cover a wide range of research topics such as tritium in the tokamak, tritium processes and waste management, plasma facing components, other fusion engineering aspects and safety. This paper reports about Plasma Facing Component (PFC), Engineering and Safety related tasks, whereas the tritium related issues of the FT activities at JET are summarised in [1].

1. INTRODUCTION

The JET facilities (JET tokamak, JET neutral beam test bed, JET active gas handling system, etc.) have been used since January 2000 under the European Fusion Development Agreement (EFDA). Scientific and Technical (S/T) tasks for experiments and technology activities are performed in various Task Forces (TF). The JET experimental campaign has focused on studies in support of the ITER physics basis [2]. As JET is the closest machine to ITER (e.g. its unique capability to handle T), taking into account its test bed facilities and the 20 years of operating experience, in Spring 2000 it was decided to launch a FT programme at JET to gain from the integration and synergism with the EFDA Technology programme.

26 S/T tasks were/are performed within FT-TF in the years 2000 to 2002 and 19 new ones are being started for the work programme 2003.

The overall supervision and monitoring of the work is organised jointly by the EFDA Associate Leaders for Technology and JET. Field Co-ordinators/Project Leaders at CSU-Garching are responsible for the programmatic co-ordination. The scientific co-ordination is executed by the JET FT Task Force Leader (TFL), while the technical and contractual co-ordination is performed by the Garching and Culham-CSU Responsible Officers. The Associations are in charge of the execution of the tasks. The JET Operator plays an important role both for the experimental (it supports the execution of the experiments/tests) and scientific use of the JET facilities.

2. PLASMA FACING COMPONENTS

The main aims of this set of tasks are to obtain, in conjunction with TF E (Exhaust), a complete view of the material transport inside the JET tokamak, improving the understanding of the behaviour of the JET in-vessel components and identifying the causes and mechanisms for erosion/re-deposition of CFC materials.

The vessel walls are eroded by sputtering due to energetic charge-exchange (CX) neutral particles. The eroded material is redeposited mainly in the divertor region and may trap hydrogen by codeposition. The knowledge of the amount of eroded material is therefore crucial for predictions of tritium inventories. CX-sputtering is also an important source of impurities released from the walls.

2.1 INTERNAL PLASMA FACING COMPONENTS BEHAVIOUR AND MODELLING

The knowledge of power and flux into the divertor during Edge Localised Modes (ELMs) is crucial for ITER (at JET during experimental campaigns only the temperature is measured). During transient high heat loads the power calculated using standard material properties is over-estimated [3]. In order to improve power estimation and provide tools for better power/energy measurements in tokamaks, model validation and experiments on divertor tiles are on-going. New material properties were introduced in the numerical simulations and will be validated. The experiments are performed at the well-controlled JET Neutral Beam Test Bed Facility (NB-TBF). Thermocouples were inserted at 5,10, 20 mm distances from the exposed tile surfaces to determine the temperature profiles in the tiles, to calculate thermal diffusion coefficients and to cross check the model with respect to the measured surface temperature and the deposited power.

A detailed 3-D model (true geometry of tiles with dumbbell, …) was developed using the CASTEM 2000 code to calculate the surface and in-depth temperature distribution on the actual JET divertor tiles during high frequency energy deposition. Different material configurations were calculated taking into account the influence of dust and flakes on the tile surfaces. The calculation will be checked by fast infrared cameras and thermocouple measurements in order to quantify the impinging heat loads.

Table I lists maximum temperatures of the tiles at various locations calculated with the model mentioned above for three different heat loads. Model M1 uses the nominal thermal properties of the CFC tile and model M2 includes a 40 mm coating layer with decreased thermal conductivity.

2.2 CHARACTERIZATION OF JET WALL TILES AND PFC WITH SURFACE ANALYTICAL TECHNIQUES

Coated divertor and wall tiles exposed in JET during the 1999–2001 operations have been used to assess erosion/deposition in the main chamber and divertor. Each tile had both mechanical markers for determination of large-scale erosion or deposition and poloidal strips of a C+10% B layer (thickness ~2.5µm) on a thin Re interlayer (thickness ~0.5µm) for smaller amounts of erosion/ deposition. The tiles were re-analysed [4] after their removal in 2001 using secondary ion mass

Table I: Maximum temperatures (initial temperature at 20°C) of the tiles calculated with two different surface models

	Flux F1 100 MW/m^2 10 ms on, 40 ms off		*Flux F2 50 MW/m^2 17 ms on, 43 ms off*		*Flux F3 5 MW/m^2 2 s on, 2 s off*	
MaximumT (ºC)	*Model M1 Bulk*	*Model M2 Bulk+Layer*	*Model M1 Bulk*	*Model M2 Bulk+Layer*	*Model M1 Bulk*	*Model M2 Bulk+Layer*
Exposed face (layer)	932	1399	856	1166	684	803
Top tile face		1043		989		787
5 mm depth	241	248	337	351	529	570
Dumble	103	103	149	148	364	367

spectrometry (SIMS), Rutherford backscattering spectrometry (RBS) and time-of-flight elastic recoil detection analysis (TOF-ERDA). The micrometer results show that the thickness of the deposits increases towards the bottom at the inner divertor wall (points 1- 8), reaching a maximum of about 90 mm. SIMS gives somewhat lower results at the inner wall.

The SIMS depth profiles of a deposit from the bottom of tile 1 are shown in Figure 1. The Re- and B-containing layers are clearly visible at the interface between the deposited film and the CFC substrate. The deposit forms two layers. The surface layer contains mostly C and Be with a high deuterium content and Ni which originates from inconel used as material for the JET vessel wall and internal metal fittings such as bolts, etc. The films underneath the surface layer are very rich in beryllium. The change in the composition between the two layers may be related to a decrease in the temperature of JET vessel walls from 320°C to 200°C in December 2000 [4].

The films on floor tiles contain mainly carbon. Very little Be is observed on shadowed surface tile areas. The deposit on the shadowed regions in the outer parts of floor tiles contains large amounts of D. High D content has also been observed earlier in flaking deposits at the inner louvres [5]. The samples from the sloping parts of the floor tiles (which are visible to the plasma – see Figure 1) have a very thick powdery deposit containing mainly carbon with low hydrogen and deuterium content, except at the surface. Between the carbon film and the substrate is a layer with quite high Be and Ni content. Samples from the part shadowed by the septum have deposits containing mostly carbon. Deuterium content is quite high in the deposits whereas Be content is low.

In the outer divertor, only small amounts of erosion/deposition were found. SIMS measurements show that in some areas there are no remaining signs of the B and Re markers, suggesting several microns erosion in these regions, whilst at some other points reduced quantities of B and Re relative to the composition prior to exposure were still present. On the other hand, the deposits are inhomogeneous both in toroidal and poloidal direction.

2.3 EROSION AND DEPOSITION IN A POLOIDAL SET OF DIVERTOR TILES

Thick deposited layers, consisting mainly of carbon with large amounts of trapped hydrogen, were observed on the louvres in the inner leg of the JET divertor since the installation of the Mark IIA divertor. The mechanism, which is responsible for hydrogen trapping at these areas far away from the plasma, is not yet clear. Thermal decomposition of soft hydrocarbon layers into hydrocarbon radicals and sticking of these radicals on cooler surfaces has been proposed as mechanism. In order to study these issues the following experiments were performed or are planned [6, 7].

2.3.1 Long Term Samples (LTS) 1999–2001

LTS of fine grain graphite covered with several 100 nm Al and Cu layers were installed in the inner main vessel walls during 1999 and dismounted in 2001. Visual inspection revealed that Al and Cu layers were completely eroded. Detailed ion beam analysis is on going.

Sticking monitors, consisting of small boxes with entrance slit, allow the determination of the sticking coefficients of different radicals and the identification of the deposition mechanism. The thickness of the deposits accumulated from 1999 to 2001 inside the cavities ranged from several monolayers to about 16μm. Different model calculations of the observed thickness distribution of the deposited layers are ongoing.

2.3.2 Long Term Samples 2001–2004

In 2001 a poloidal set of 6 divertor tiles coated with a stripe of W, used as marker for the determination of deposited carbon, were installed in JET after their characterization. Additionally, W allows the identification of net erosion areas which are the source of carbon which finally forms the codeposited layers. Spectroscopic measurements of the WI-line (light emitted from transitions between the ground and excited states for the neutral W atom) at 429.5 nm, during the early stage of the C5-campaign, showed that the WI-light is below the detection limit.

New LTS and sticking monitors have been installed after their compositional and dimensional characterisation.

Figure 2 shows the positions of two sticking monitors within the MkIIGB divertor.

3. ENGINEERING

Of the various existing fusion devices JET is closest to ITER in size and design. Therefore its operating experience and the capability of its systems constitute an important reference point for the ITER design and open issues of ITER technology.

Four tasks are ongoing until now covering topics such as remote handling, optical fibres, characterization of ITER bypass switch and in-vessel inspection technique using laser. Further tasks could be launched to give important contributions to ITER designers, e.g. with respect to plasma disruptions analysis, diagnostic and control/mitigation if an Association interested in performing these studies can be found.

3.1 IMPLEMENTATION OF OPTICAL FIBRES IN DIAGNOSTICS OR INSPECTION SYSTEMS

Compare to JET, intense radiation filed generated in ITER will significantly reduce the optical transmission capability of glass material used as plasma diagnostic devices [9]. To cope with these negative radiation effects, a promising approach relies on the hydrogen loading technique of silica glass fibre. To evaluate and demonstrate the reliability of hydrogen loaded silica glass, ITER optical fibre candidates [10] will be tested at JET. These optical fibres will be installed in an enhanced diagnostic at JET, the charge-exchange diagnostics, to test and characterise their performance in a representative Tokamak environment.

The operating experience with optical fibres during the D-T campaigns at JET and TFTR [11] revealed that heating Si-Si fibres to 300ºC reduces the induced adsorption by at least a factor of 100. This remedial action is adequate for all JET operation scenarios.

3.2 LESSON LEARNED FROM JET MAINTENANCE AND REMOTE HANDLING OPERATION

For ITER, all in-vessel activities and part of the ex-vessel activities have to be performed fully remotely. After the D-T campaign at JET, the in-vessel activities were executed remotely due to the high radiation levels and to meet the ALARA (as low as reasonable achievable) criteria whereas all ex-vessel activities were performed by operators.

During the 2001 shutdown the following activities were done remotely at JET [12]: removal of divertor septum and installation of septum replacement plate, upper inner wall reinforcement and protection, sub-divertor flakes/dust collection, in-vessel divertor wiring test, replacement of beryllium evaporator heads, installation of protection plates and replacement of a damaged LHCD antenna tile. A compilation of the operating experience gained along the years from the several remote handling (RH) activities at JET is on going. This report can be a useful reference for ITER RH designers.

3.3 ITER BYPASS SWITCH TEST

The purpose of the tests was the verification of the commutation performance of the bypass switch designed for the ITER discharging networks (e.g. to discharge the energy stored in the superconductive coils when a quench is detected). The tests were carried out in the Toroidal Field Test Cell supplied by the Toroidal Flywheel Generator Converter during the June 2002 JET shutdown.

200 pulses were performed with full current (between 60 kA and 75 kA). The bypass switch was opened and the current commutated to the parallel vacuum switch. The main parameters checked were potential damage and wear of the main and sacrificial arc contacts, the total resistance and switching times. During these tests the current through each of the 12 sacrificial contacts was monitored. This required the installation of new Rogowski coils and transmitters.

The tests were performed on time and the switch met the test requirements.

3.4 LASER IN VESSEL VIEWING SYSTEM (LIVVS)

The aim of this task is to develop and install a tool able to supply high quality images of the JET in vessel components with laser techniques, which is capable to work in a hostile environment such as in ITER. This view is important during the operation of a tokamak to check the in-vessel components and, in case of metrology capability, to determine dimensions and orientations of the in-vessel components before RH activities.

The installation of LIVVS at JET has been deferred because the JET Quality Assurance (QA) requirements were not fully met and the quality of the images did not fulfil the specifications, partly due to the stringent operating conditions (high vacuum and 350ºC). Corrective actions are on going.

4. SAFETY

The presence of tritium, the considerable activation during the D-T campaigns and the extensive experience in operating key components whose failure can be the initiating event of an accidental sequence in a fusion reactor are just a few examples of the importance of the JET experience towards ITER design or validation of ITER choices.

4.1 NEUTRON ACTIVATION MODEL

Calculations have been performed to model the neutron transport throughout the JET installation using MCNP™, a Monte-Carlo particle transport code. A very detailed computer model of the tokamak, the torus hall and the associated additional heating and diagnostic systems has been created. This model together with the MCNP code was used to determine the neutron flux as a function of energy at 32 locations at which activation foils packs (ACP) had been placed during JET's DT experiment in 1997. These neutron spectra were used as input to the inventory code FISPACT to calculate the levels of activation in the foil. The technique can determine the neutron activation level at any point in the torus hall to within a factor of two. Figure 3 shows the C/E (i.e. the ratio of calculation to experimental observed activation). The first three groupings of data points (Inner, limbs and wall) are sensitive to thermal neutrons. The second (smaller) set is not sensitive to thermal neutrons because the thermal flux was removed by wrapping the activation foils in Cadmium. The activation calculated from the model can be used as input for the database that is used to plan shutdown, decontamination and disposal of various components [13].

The same model has been used for estimates of the gamma dose inside the vessel, which arises from activation of the machine itself. These have been compared with health physics measurements and agree within the experimental and calculation error bars (~20%). At positions close to the neutron source the combination of MCNP™ and FISPACT can be used to calculate the gamma dose within the vessel to better than 30%. This has demonstrated that it is possible to determine the dose with sufficient precision to allow safe and economic planning of work inside the vessel.

4.2 JET OPERATION EXPERIENCE. COLLECTION OF COMPONENTS FAILURE RATE DATA

A reliability and availability analysis of ITER systems is necessary for design and licensing purposes. There are several failure rate data originating from nuclear and industrial systems, but not from nuclear fusion devices. Useful data can be extracted from the 20 years of JET operation.

The objective of this task is to develop a fusion-specific data compilation (i.e. component failure database) with data originating from operating experiences gained at JET and at Tritium Laboratory Karlsruhe (TLK). A functional analysis, categorisation and compilation of maintenance/failure rate statistics under the perspective of the ITER design requirements will be the final result.

The retrieval of all information available about single component malfunctions and failures of the Vacuum and Tritium Systems is on going. Causes, consequences, maintenance actions (repairing, substitution, etc.) are pointed out together with information useful to evaluate probabilistic values related to component malfunctions and failures. Other data have to be evaluated regarding plant operations (e.g. components working time) and design (e.g. operating mode, total number of similar components). The gathered data will be treated to evaluate probabilistic values. The results will be recorded in the 'Fusion Component Failure Rate Database' and will be available to the fusion scientist community.

Similar data exist for other systems like Power Supply, Additional Heating and CODAS systems. Equivalent failure rate database will be developed within the FT work programme for 2003.

CONCLUSIONS

Fusion Technology activities at JET, launched in April 2000, provide relevant contributions to JET operation and ITER design in the areas of tritium distribution in the Tokamak; Tritium processes and waste management, plasma facing components, engineering and safety. Until now, 27 S/T tasks have been undertaken, while 19 new ones are due to start in the frame of the Workprogramme 2003.

FT tasks at JET are progressing well. A few FT tasks face delays due to the re schedule of the JET operation plan and JET QA requirements.

The tasks related to tritium play the major role (about 70%) in the FT programme. PFC, Engineering and Safety are further important issues. Part of the on going tasks within these topics was briefly addressed in this paper. They all are especially important both for the operation and decommissioning of JET, for the design and operation of ITER as well as for licensing aspects.

The main aims of the further development of the FT activity at JET in 2003 and beyond are:

- Demonstration of ITER/JET relevant tritium technologies;
- Studies for a detailed design of a water detritiation plant for JET and ITER;
- Demonstration of efficient and economic disposal routes of further tritium contaminated waste categories for JET and ITER;
- Characterisation of PFC/Be First Wall behaviour;
- Collection and interpretation of further JET operating experience data for ITER engineering design and safety analysis.

ACKNOWLEDGEMENTS

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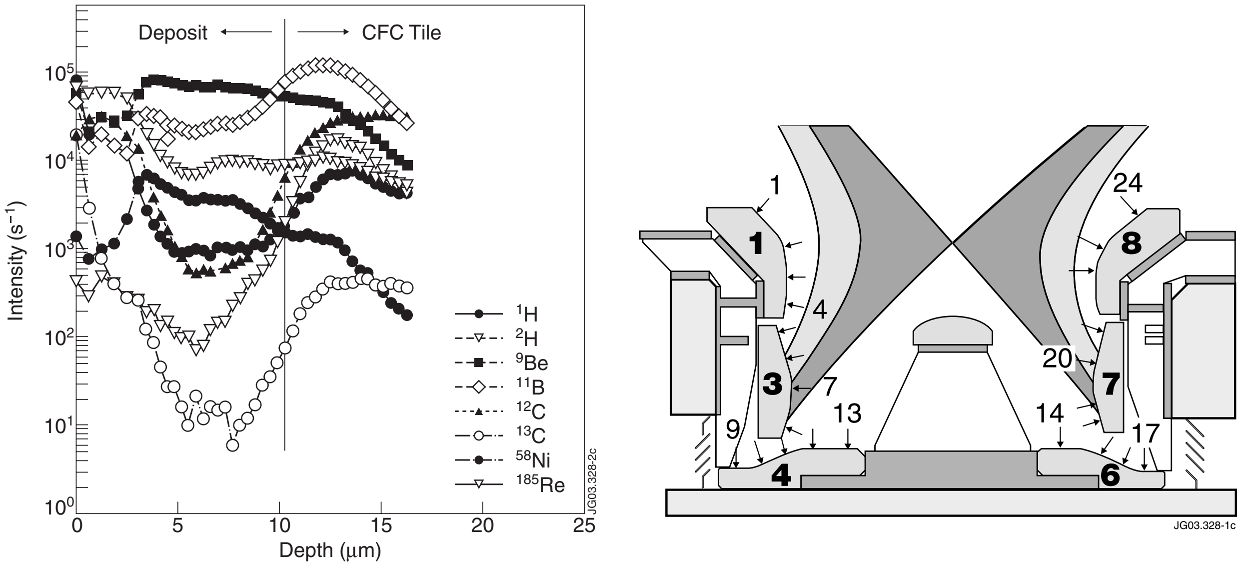

Figure 1: SIMS depth profiles from the bottom of tile 1 (JET MK II GB Divertor). Interface between the deposit and CFC substrate is also shown.

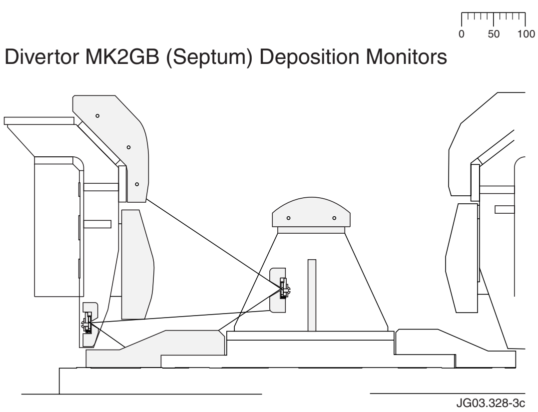

Figure 2: Divertor MK2GB (Septum) deposition monitors.

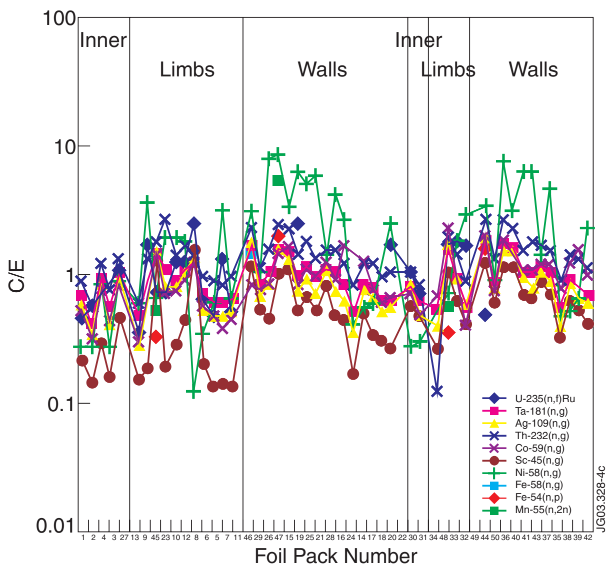

Figure 3: C/E values for all foils and all AFP.