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ABSTRACT

Among the technological activities performed at JET in support of the scientific objectives of both JET and ITER, a significant effort is devoted to the investigation of the erosion, transport and deposition of wall materials, and of their fuel retention properties. With the analysis of wall tiles retrieved in the 2010 shutdown, the full characterization of the previous JET carbon wall is obtained. In order to confirm the expectations on properties of the new ITER-Like Wall (ILW) installed in 2011, a large number of marker tiles and profiled tiles have been prepared and installed both in the main wall and in the divertor. These will be retrieved from the vessel during a short shutdown at the end of 2012 and analysed. The major changes introduced by the new ILW materials in JET required also a new nuclear characterization of the machine. Neutronics measurements have been performed to obtain the neutron/γ-ray field changes inside and outside the JET machine. The experimental data are also used to validate neutronics codes used in ITER design. A new calibration of neutron detectors, scheduled in the 2012 shutdown and adopting the same procedure as in ITER, has been prepared based on extensive neutronics calculations.

1. INTRODUCTION

The JET research program includes technological activities in support of the scientific objectives of both JET and ITER. To this purpose, in 2010-11 the JET machine has undergone a major change to replace the previous carbon wall with a new ITER-Like Wall (ILW) making use of beryllium and tungsten in plasma facing components [1].

The erosion/deposition of wall materials in JET is characterized by net erosion on the main chamber wall and outer divertor, and migration of eroded material mainly to the inner divertor. During the 2009-10 shutdown phase, dust was collected from JET vessel [2] and several removed tiles were selected for analysis of deposits and surface. In this paper, first results of analyses on tiles exposed in 2007-2009 are presented. Considering also all previous results of erosion and deposition studies, a full characterization of the C wall in JET will be derived for comparison with the new ILW.

Presently, one of the major objectives of the JET program is the investigation of the wall material transport, erosion/deposition and the fuel retention properties in the ILW. It is expected from laboratory experiments that the main mechanism for the fuel retention in the ILW is co-deposition in Be-layers. Implantation is the main mechanism for the retention in W, but it is expected to play a negligible role in comparison with the Be co-deposition. In order to confirm these expectations, and the results obtained during first ILW plasmas from gas balance method [3,4], a large number of marker tiles, profiled tiles, dust collectors and test first mirrors have been prepared and installed both in the main chamber and in the divertor. Post mortem analyses will be performed on some of these tiles to be retrieved from the vessel during a short shutdown at the end of 2012.

The major changes introduced by the new ILW materials in JET required also a new nuclear characterization of the machine. Neutronics analyses have been performed to calculate the neutron/γ-ray field changes inside and outside the machine, the material activation and the shutdown doserate after DD and DT operation. A new calibration is needed for neutron detectors, based on the use of a ^{252}Cf neutron source moved inside the vessel, and similar to the one that will be adopted in ITER, whose preparatory design has required extensive neutronics calculations. The combination of neutronics calculations and measurements provides a validation of the neutron monitor calibration procedure adopted in ITER, as well as of neutronics codes and nuclear data used in ITER nuclear design.

2. EROSION / DEPOSITION STUDIES AND FUEL RETENTION

Prior to the installation of the ILW, JET has been an ”all- carbon” machine since the installation of the divertor in 1994 as all the plasma facing components were made of carbon (mainly carbon reinforced composite (CFC)). However, just over half of the vessel wall was covered with carbon tiles whereas the uncovered areas were made of Inconel. Detailed studies have been performed after each operation campaigns showing that material is eroded from outer divertor and vessel walls.

A cross-section of the JET divertor MkII-HD used throughout the period 2005-2009 is shown in Figure 1(a). A number of tiles where selected for post mortem analyses from those removed during the latest shutdown for the installation of the ILW in 2009-10. As a general result, heavy material deposition is found at the inner JET divertor whereas most areas at the outer divertor exhibit little erosion [5]. Eroded material consists mainly of carbon and beryllium flows around the scrape-off layer (SOL) from outboard to inboard side, and deposits in the inner divertor tiles 1 and 3 together with hydrogen isotopes from the plasma. Carbon is subsequently chemically sputtered from the inner divertor deposits, leaving behind films rich in beryllium and other metals that cannot be chemically sputtered, and is transported to regions shadowed from the plasma, such as the inner louvres, where large amounts of hydrogen isotopes are trapped in the deposits. The Be-rich and Ni-rich layers on tiles 1 and 3 have high Be/C ratios, the largest values being at the surface of the deposits near the bottom of tile 1 and top of tile 3. The average Be/C ratio over tile 1 has almost doubled on tiles removed in 2010 compared with tiles removed in 2004. This is the region of the inner strike point during the high triangularity discharges that formed a significant part of the 2007-2009 operations. The increase in the Be/C ratio could be due to the increased number of high triangularity discharges.

Base tiles 4 and 6 show typical deposition pattern with a thick co-deposited layer on the sloping parts and in the shadowed regions. In the case of tile 4 the highest fuel amount is in the shadowed region (shadowed by tile 3), but there is an increased amount of deuterium near the edge facing the LBT tile. The co-deposited layer on tile 4 contains also some beryllium. The highest beryllium content was found at the bottom of the sloping part which is the limit of area that can be accessed by the confined plasma. The beryllium content is, however, only half of the beryllium amount observed on tiles removed in 2007 [5]. The reduced beryllium amount on tile 4 removed in 2010 could perhaps be due to the larger fraction of high triangularity discharges in which beryllium is deposited mostly on tile 1. Base tile 6 has also high deuterium content in the shadowed region (shadowed by tile 7) and on the inboard side facing the LBT tile. Beryllium profile has, however, two peaks across the tile. This double peak in the beryllium profile has been observed earlier and it has been shown to correspond roughly to the most favoured positions of the outer strike point [5]. During the 2007-2009 operations about 20% of the discharges had the outer strike point on the LBT tile. Post-mortem analyses indicate that there is some carbon deposition on the outboard side of the tile but otherwise the tile is relatively clean. Some of the carbon deposition occurred during the last day of operations due to the $^{13}CH_4$ puffing experiment.

The outer divertor tiles 7 and 8 are normally in a region of slight net erosion and the tiles appear clean. However, there is a pattern of ^{13}C deposition on the tiles removed in 2010, with the largest concentration ($\sim 10^{17}$ atoms cm^{-2}) occurring at the bottom of tile 7, decreasing by two orders of magnitude at the tile 7/tile 8 junction, and rising again to $\sim 10^{17}$ atoms cm^{-2} at the top of tile 8. This indicates that the $^{13}CH_4$ puffing made at the end of 2009 operations may have changed conditions in the SOL temporarily into a deposition zone.

A complete global balance for carbon in JET will give insight into the lifetime of PFCs and into the fuel retention. Carbon balance in JET for the 2007-2009 operations has been determined by calculating the mass of eroded carbon in the main chamber and comparing it with the mass of carbon found in the form of deposits and dust in the divertor [2].

Figure 1(b) shows the summary for erosion and deposition. The results are based on tile profiler, optical microscopy and ion beam results. Deposition occurs mainly at the floor tiles 4 and 6, whereas main erosion sources are the inner wall guard limiters and upper dump plate area. Extrapolations from local measurements of erosion and deposition give a net erosion for the entire main chamber of about 436 g and a net deposition in the divertor of about 533 g, upon which the amount of dust collected (~300 g) has to be added. The amount of the net deposition is thus about twice as large as the amount of the net erosion. Considering the sources of uncertainties in scaling the results from representative tiles to the whole torus, the agreement within a factor of two is acceptable. The results for the material balance provide a benchmark for comparison of erosion and deposition between “all carbon” and “all metal” scenarios in JET.

A long lifetime of plasma-facing components and keeping retention of plasma fuel at acceptable levels are key elements for successful operation of ITER [6]. During the 2007-2009 campaign the total deuterium input was ~2.3 kg, while the total deuterium retention in the divertor tiles is estimated to be ~233g which corresponds to a retention of ~10 % [7].

Most of the deuterium is trapped on inner divertor tile 4 (~40%) and outer divertor tile 6 (~28%). The long-term deuterium retention fraction evaluated from integrated gas balance (~10–20%) for various devices is larger than the deuterium retention deduced from the post-mortem analysis of tiles [8]. There are limitations in both techniques and it can be concluded that post-mortem analyses tend to underestimate the deuterium retention whilst gas balance overestimates it.

In 2010 JET was converted to an “all-metal” machine with ITER-like material choice on the wall (beryllium) and at the divertor (tungsten). Post mortem analyses will continue to support the investigation of the wall material transport, erosion/deposition and the fuel retention properties in ITER wall materials. To this purpose, a set of marker coated tiles have been prepared, profiled, analyzed by ion beam techniques (IBA) and installed during the 2010 shutdown. These tiles will be retrieved in 2012 after exposure at JET plasma and post-mortem analyzed (Fig. 2) to provide erosion rates and fuel retention data.

Beside H/D measurements, experimental techniques based on Full Combustion combined with scintillation method and on Accelerator Mass Spectrometry are being developed to measure the depth profile of tritium retained in samples of plasma facing materials. An absolute cross calibration has been performed between the two methods using samples exposed at JET plasmas, particularly in view of the ILW and of a new DT campaign (DTE2). The comparison of results on samples exposed during 2007-2009 campaign shows a very good agreement within ±10% [9].

In parallel, the limits of W coating on CFC substrate divertor tiles, subject to thermal cycling during JET pulses, have been investigated. The carbidization of the tungsten due to the diffusion of the carbon from the substrate have been recognized as mechanisms for degradation of the coatings and may affect the fuel retention in the ILW. Results of these investigations are presented in this Symposium [10].

3. NEUTRONICS STUDIES

One of the consequences of the installation of the ILW is the change in the neutron flux mainly due to the introduction of Be and of W. The 2.5 MeV neutron flux is reduced by about 20% at the inner irradiation end due to increased elastic scattering because of the presence of Be. The neutron multiplication due to the (n,2n) reactions on Be and other nuclides is negligible in DD operation but is evaluated to be $> 25\%$ in DT operation. This is reflected also in the response of calibrated neutron monitors that provide the absolute fusion reaction rate, i.e. the fusion power. The neutron monitors have been calibrated before the JET start-up in the 1980s. Since then, the machine has been significantly changed with the introduction of, e.g the divertor, RF antennas and limiters, and finally the ILW. A new calibration of the neutron monitors, fission chambers and activation system, is now required and will be performed during the 2012 shutdown using an intense ^{252}Cf neutron source moved inside the vacuum vessel by means of the JET Mascot robotic boom. The source will be located at more than 200 toroidal/poloidal positions to simulate the volume plasma source (Fig.3). Extensive neutron transport calculations have been performed using MCNP code and detailed JET 360° models to obtain the detector response functions in plasma operations from calibration conditions, including the effect of the mascot robot holding the source, the different position of large items outside the torus and other differences [11]. Recent calculations have shown that when weighting on the importance function, the detectors located far from boom entrance port are practically not affected while the one closest to it is affected by less than 5% (Fig.4b) [12]. An important and explicit objective of the calibration procedure, which is the same as that planned in ITER, is to quantify and possibly reduce sources of uncertainties, and assess the accuracy achievable in neutron monitor calibrations in tokamak environment. It is planned to repeat the calibration for the DT campaign using a 14-MeV neutron generator (tube) as envisaged in ITER.

Apart from neutron monitor calibration, neutronics experiments have been carried out at JET with the purpose of providing useful data for JET operation and, at the same time, allow for validation of codes used in ITER design. During the last shutdown dedicated to the installation of the ILW, shutdown dose rates have been measured with different dosimeters along the axis of the Octant 1 main horizontal port, from the plasma centre to 1 meter outside the port, starting from 81 days up to 263 days after shutdown. During this time interval, the dose rate decreased from 270μSv/h to 165μSv/h in the vacuum vessel centre, and from 2μSv/h to 1μSv/h at 1m distance from open port door. The measured values have been compared with dose rates calculated using both the Advanced-D1S method [13], in which new computation capabilities have been introduced, such as the dose rate spatial mesh map and the automated time dependence of the dose rate, and the novel R2Smesh method utilizing the MCNP5 mesh tally capability [14]. In these calculations, the geometrical models referred to the old JET carbon wall (Fig. 5). With few exceptions, A-D1S and R2Smesh calculations predict the measured values within the experimental uncertainties (±30%). However, A-D1S and R2Smesh results show a discrepancy in the time profiles, probably due to different calculated contributions of the ^{58}Ni(n,p)^{58}Co and ^{59}Co(n,γ)^{60}Co reactions, characterized by 70.8 days and 5.27 years half lives, respectively.

Recently, new A-D1S calculations showed that the effect of ILW on in-vessel shutdown dose rate is moderate at medium cooling times, generally by less than -20%, although higher impact could be expected at longer times after shutdown. The doserate measurements will be repeated in the 2012 shutdown, after the ILW campaign, using also γ-ray spectrometers and dosimeters at additional locations.

Presently, the technology program also includes the preparation of a number of experiments in view of the exploitation of a new DT campaign at JET (DTE2, planned in 2015), taking advantage of the use of tritium and of the production of a large 14 MeV neutron yield. In fact, assuming that more than 10^{20} neutrons would be produced during the DTE2, a 14 MeV neutron flux in excess of 10^{12} n/(s·cm^2) and fluence in excess of 10^{14} n/cm^2 on the first wall can be obtained (close to ITER), which are significantly larger than those achievable in reasonable irradiation time in any other existing experimental facility, including accelerators. The unique 14 MeV neutron yields produced in DTE2 should therefore be exploited to validate codes, assumptions, procedures and data currently used in ITER design thus reducing the related uncertainties and the associated risks in the machine operation. To this purpose, experiments are being prepared to measure the shutdown dose rates around the machine, the neutron/γ-ray field outside the machine and the radiation streaming in the ducts and labyrinths in the tokamak hall, the production of activated products in the cooling water, the activation of real ITER materials using samples of the vacuum vessel, divertor and other locations, the radiation induced effects on in-vessel sensors and on out-vessel fiber optics (FOCS). The measurements will be compared with predicted values used the state-of-art simulation codes. Further issues could be investigated to meet ITER needs.

CONCLUSIONS

The on-going analysis of wall tiles retrieved in the 2010 shutdown is providing the full characterization of the erosion, transport and deposition of the previous JET carbon wall. In parallel, a large number of ILW marker tiles and profiled tiles have been installed in 2011 both in the main wall and in the divertor in order to confirm the expectations on properties of the ILW. These will be retrieved from the vessel during a short shutdown at the end of 2012 and post-mortem analysed. The major changes introduced by the new ILW materials in JET required also a new nuclear characterization of the machine: a new calibration of neutron detectors, scheduled in the 2012 shutdown and adopting the same procedure as in ITER, has been prepared based on extensive neutronics calculations. Measurements have been performed to obtain the neutron/γ-ray field changes inside and outside the JET machine. The experimental data are also used to validate neutronics codes used in ITER design. Presently, the technology program also includes the preparation of a number of experiments in view of the exploitation of a new DT campaign at JET (planned in 2015), taking advantage of the use of tritium and of the production of a large 14 MeV neutron yield.

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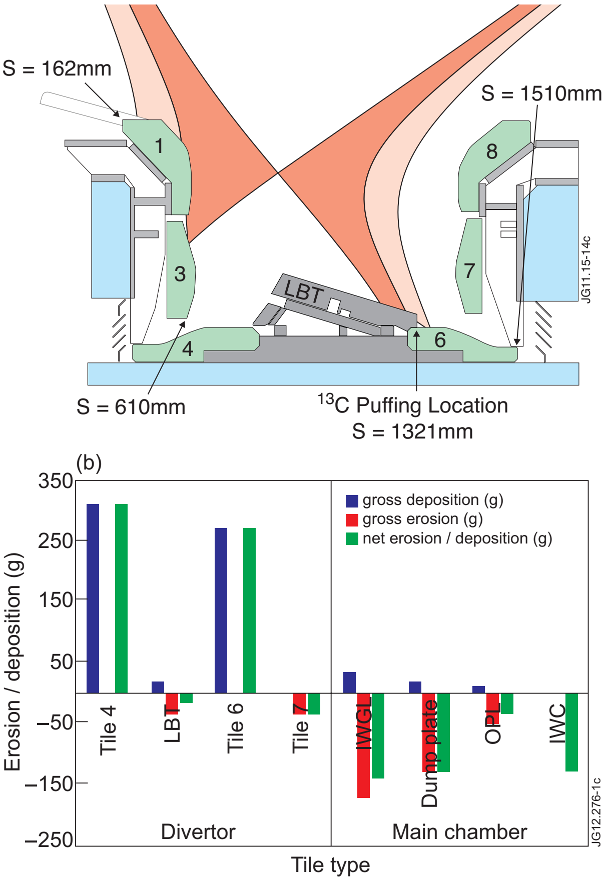

Figure 1. Cross-section of the MkII-HD divertor (a) and summary of erosion and deposition at JET during the 2007-09 operations (b).

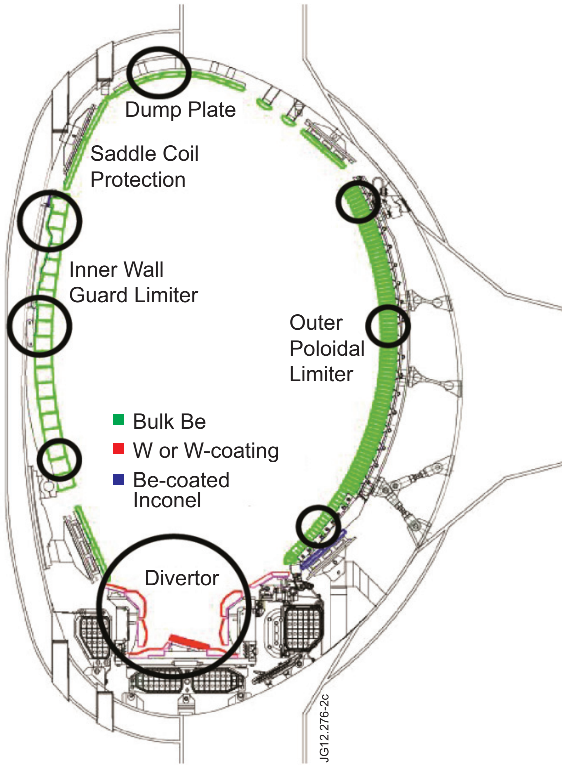

Figure 2: JET vessel. Circles indicate the location of marker tiles.

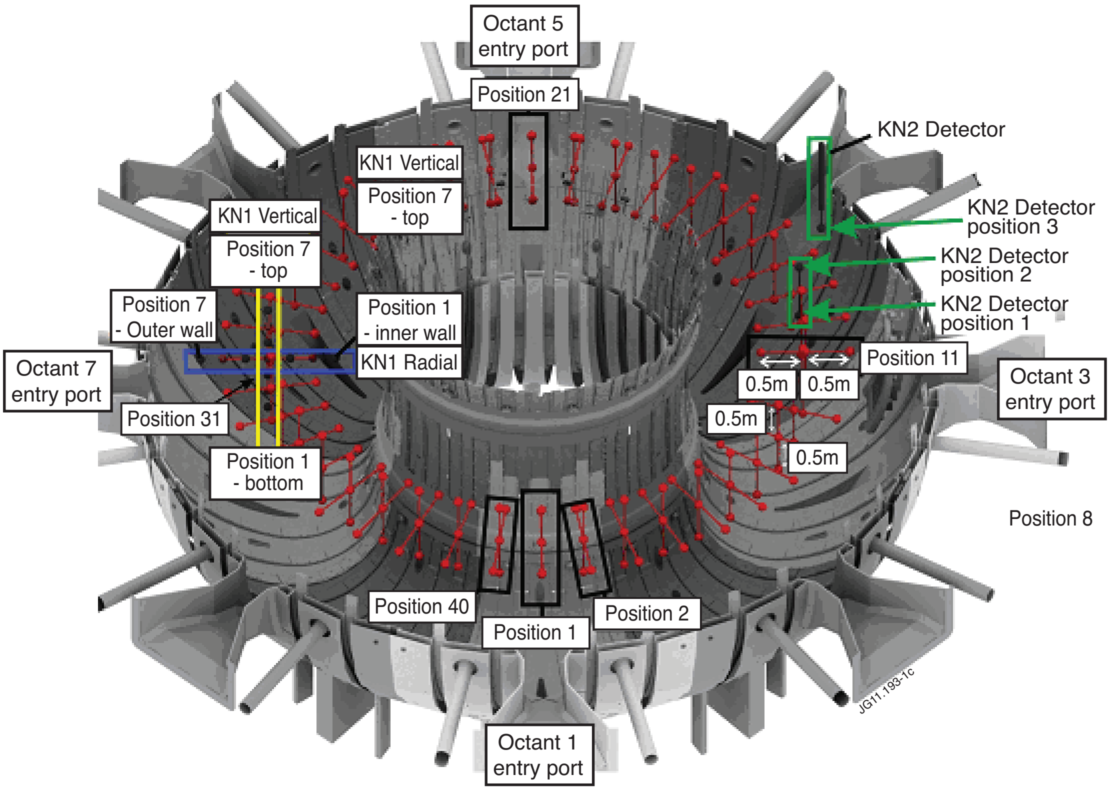

Figure 3: Locations of the 252Cf source for neutron monitors calibrations. KN1 denotesexternal neutron monitors and KN2 denotes the JET neutron activation system [11].

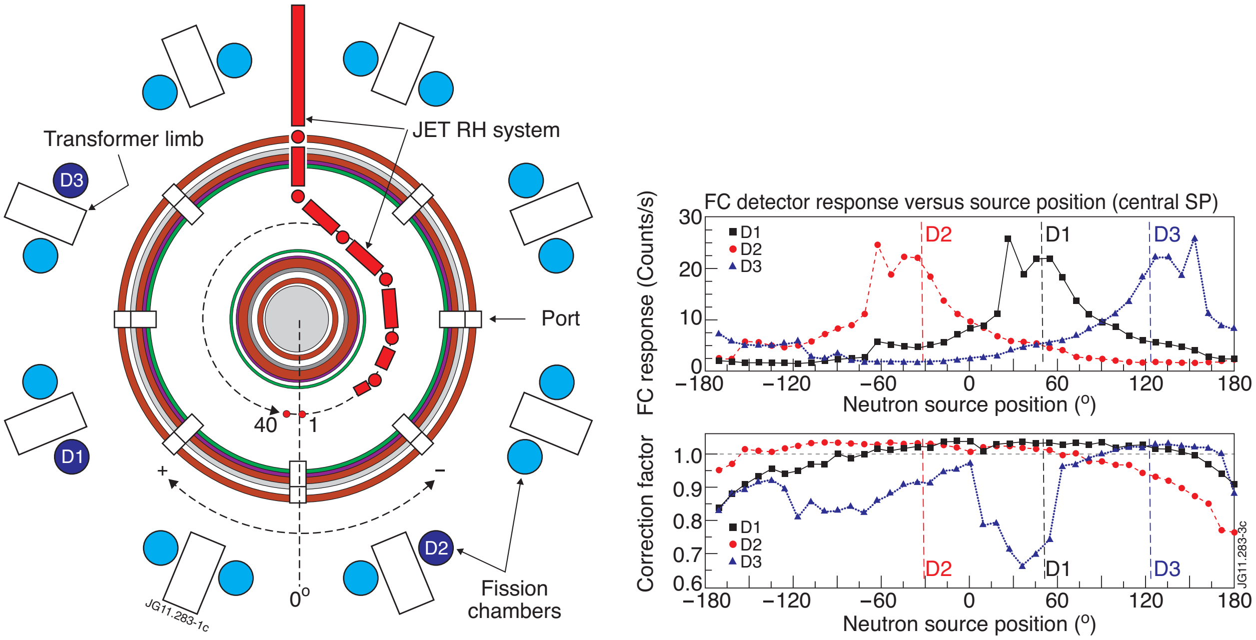

Figure 4: (a) Horizontal section at midplane of the MCNP model of JET, showing the robotic boom deploying the ^{252}Cf source in position 1 (the manipulator is tilted with respect to the plane and is not visible). D1, D2 and D3 denote the positions of the external neutron detectors (fission chambers). (b) Response of fission chambers located in D1, D2 and D3 positions as function of source position on axis (above) and correction factor due to the presence of boom and manipulator (below).

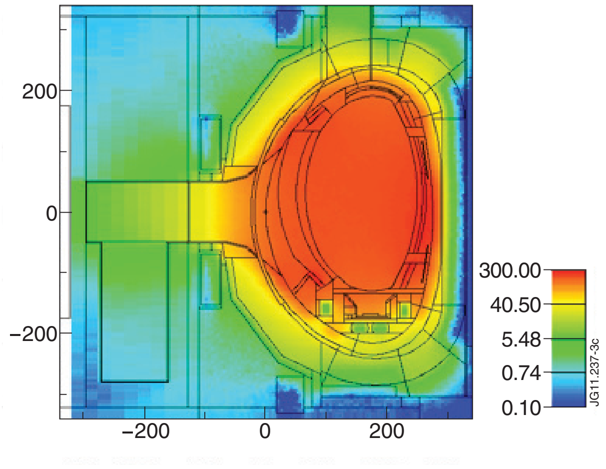

Figure 5: Dose rate mesh map in μSv/hr at 81 days after shutdown calculated by A-D1S superimposed over the middle radial poloidal section of JET tokamak [13].