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Shutdown Dose Rate Benchmark Experiment at JET to Validate the Three-Dimensional Advanced-D1S Method

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(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

ABSTRACT

The paper describes a new benchmark, performed as a preliminary experiment on JET tokamak during the last shutdown. Dose rate has been measured with different dosimeters along the axis of the main horizontal port of Octant 1, from the plasma centre to 1 meter outside the port at various times after shutdown. The activation dose from the horizontal neutron camera, moved outside the torus hall during the shutdown, has also been assessed. The measured values have been compared with dose rates calculated using an Advanced-D1S method in which new computation capabilities have been introduced, such as dose rate spatial mesh map and automated time behaviour.

Measurements along the axis of the horizontal port are well predicted by the calculation. With few exceptions, the D1S estimation is within the error of the measurements. The activation of the horizontal camera is underestimated by a factor of 2. However more accurate measurements are needed to reduce the uncertainties.

The Advanced-D1S method, the results and implications of the benchmark are presented and discussed.

1. INTRODUCTION

The prediction of the shutdown dose rate induced by neutron activation is a major safety task for fusion reactors, as part of planning the operations of intervention and maintenance in order to guarantee respect of the dose limits.

The development and improvement of calculational methods for three-dimensional shutdown dose rate predictions are in progress [1-7]. The Direct One Step (D1S) [1-3] method is an original approach based on the combined use of the MCNP [8] Monte Carlo code and the FISPACT [9] inventory code. D1S is based on the assumption that the decay gammas of the radioactive nuclides are promptly emitted and hence, the neutrons and decay gammas are transported in a single Monte Carlo simulation. The time correction factors required to take into account the build-up and the decay time of each radionuclide are calculated using the inventory code.

During the last decade D1S, as well as the conventional rigorous two-step (R2S) method [4-7], has been extensively used and several benchmarks have been performed [10-13]. Satisfying results were obtained in the ITER oriented experiment at the Frascati Neutron Generator [10]. However, a validation in a reactor-like configuration, such as the JET tokamak is necessary in order to assess the dose prediction reliability in ITER. The past benchmarks conducted on JET showed discrepancies between calculation and measurement because of the rather high uncertainties of the measurements and the inadequacy of the MCNP modeling, especially in positions far from the vessel [11-13].

The paper describes a new benchmark, performed as a preliminary experiment on JET during the last shutdown for the installation of the ITER-like wall. Dose rate has 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 and at various times after shutdown. The activation dose from the horizontal neutron camera (KN3 system) which was, moved outside the torus hall during the shutdown, has also been assessed. The measured values have been compared with dose rates calculated using an

"Advanced-D1S" method 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.

The Advanced-D1S method and the results of the benchmark are presented and discussed in this paper as well as the implications for future applications.

2. DOSE RATE MEASUREMENTS

2.1 DOSE RATE METERS

Dose rate along the axis of the main horizontal port of Octant 1 has been measured using two Geiger Müller type detectors. An Automess Teletector 6112D (energy range 80keV-2MeV, dose rate range 0.01µSv/h - 9999mSv/h) and a Mini Rad series 1000R (energy range 50keV-1.25MeV, dose rate range 0.1-1000µSv/h) were used. Additional measurements inside the plasma chamber have also been performed using a ionization chamber Eberline R02-W type (energy range 20keV-1.3MeV, dose rate range 0-50mSv/h) mounted on a mascot system. For survey of the horizontal camera the Mini Rad was used.

The detectors were calibrated in terms of ambient dose equivalent, H*(10), using Cs-137 gamma source accordance with ionizing radiation regulation by radiological calibration service. For this preliminary experiment the dosimeters commonly applied for radiological protection survey at JET have been used. In a future benchmark more accurate detectors with proper calibration and better-known responses will be employed.

2.2 EXPERIMENTAL SETUP

The 2009 shutdown at JET started on October 23rd and one month later the radial neutron camera was moved outside the torus hall.

Because of access limitations, measurements along the horizontal port axis started on 12th January 2010, 81 days after the shutdown. The dose rate has been measured at different positions up to 263 days after shutdown. Dose measurements with Teletector have been performed at five positions from the plasma center to 1m outside the port door located at ~7.35m from the central axis of the tokamak (figure 1). In order to measure the dose at the centre of the plasma the Teletector detector has been extended up ~ 4.6m from the port door.

The Eberline dosimeter has been mounted on the mascot robot to carry-out a normal in-vessel survey, which was linked to our main measurements. Four mid plane measurements were performed at 85 (January 15th) and 145 days (March 17th) after shutdown in Octants 2, 4, 6 and 8.

The MiniRad has been used for dose rate measurements from 1 m outside to 60cm inside the port at 109, 137 and 263 days after shutdown and for the horizontal neutron camera survey at 95 days after shutdown.

2.3 RESULTS

The results of the dose measurements performed with Teletector and Mini Rad detectors are

summarised in table 1. After 81 days after shutdown the dose at the plasma centre was 270μSv/h. It dropped to 2μSv/h at 1m outside the port. The Mini Rad measurements were systematically lower than the Teletector measurements (ratio Mini Rad/Teletector in the range 0.40-0.8). This can be due to the different sensitivity of the detectors to gamma rays of different energies that can produce different dose rate numbers.

The additional measurements with the Eberline dosimeter inside the JET vessel estimate lower doses with respect to the Teletector. The average dose rate value on January 15th was 176μSv/h (the average of the four values in Octant 2, 4, 6 and 8). It is interesting to note that the highest value in the in-vessel measurement set was ~240μSv/h, on the surface of the antenna in Octant 6. The average dose on March 17th was 135 μSv/h. The main difference with Teletector is due to the different energy sensitivities.

Taking into account the features of the detectors used and their calibration errors, the obtained results have large uncertainties. By excluding the positional error, a relative error on high dose results of ± 30% and an absolute error of ± 1μSv/h for low doses have been estimated. The uncertainty on the central position was about ±20cm and ± 5cm elsewhere.

Concerning the survey of the KN3 system front surface, the dose rate pattern was roughly consistent with crude imaging of the plasma profile. The higher dose rates after 95 days after shutdown was ~5.5μSv/h between the central collimators on the right side[1], falling to ~ 2.5μSv/h on the uppermost and to 4.5μSv/h on the lowermost collimator hole region. A strip about 25cm wide on each side of the collimator strip showed about 2μSv/h. Out near the edges of the front face it was ~1μSv/h. The dose rate on the sides was lower than 0.5μSv/h.

3. DOSE RATE CALCULATIONS
3.1 ADVANCED-D1S
The calculation of the shutdown dose rates has been performed using the Advanced D1S method. In this improved version, the MCNP code has been modified in order to calculate the time evolution dose rate profiles in a single run and the dose rate mesh maps for interactive dose survey. The neutron and decay gamma, treated as prompt, are transported in a single MCNP run. For mesh tally maps, the time correction factors which take into account the production and decay of each radionuclide, are included in the MCNP simulation. During the Monte Carlo simulation, the time correction factors calculated by FISPACT are read on an external file. These factors are internally applied to each generated photon according to its parent and multiplied by the corresponding flux-to-dose conversion coefficient as to provide directly, as an output result, the dose rate in μSv/h. Time behaviour, at the moment implemented for standard cell or surface tallies only, is obtained by including the decay constant for each radionuclide contributing to the dose.

In the present application, the original MCNP 45° geometrical model of Octant 1 has been modified according to the real masses and volumes of JET main components [15] and including

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[1] *The asymmetry is due to the rotation of the adjustable collimators.*

the material chemical compositions with impurities [16]. Reflective boundary conditions on the lateral sides have been used to take into account full 3D transport. The model is described in the next section.

The Deuterium-Tritium (DT) and Deuterium Deuterium (DD) neutron sources were described by a parametric representation of a typical JET plasma emissivity used as reference for JET MCNP calculation [14]. It has been verified that under JET conditions the production of the radionuclides responsible of the dose rate is proportional to the flux and in such a case the total dose can be linearly decomposed in the two components (DD and DT). The decay gamma time correction factors have been calculated with FISPACT using both DD and DT irradiation scenarios based on the neutron yield data provided by JET, as described in section 3.3.

In order to calculate the shutdown doses expressed in terms of the calibrated quantity, the fluence-to-H*(10) conversion coefficients taken from ICRP 74 [17] have been used.

The used data libraries were JEFF 3.1.1 for transport and EAF 2007 for activation. On the basis of preliminary evaluations and past experiences [13] only a limited number of reactions were considered for activation. Gammas from the decay of Co-58, Co-60, Mn-54 and Ag-110m were identified as the dominant contributors to the doses. It has been verified that other nuclides give a very low contributions at these times after shutdown.

In the present simulations the replacement of the components was disregarded. This means that all the JET components described in the model are exposed to neutron irradiation for the whole JET life. This inexact assumption can be considered suitable for the present analysis because the major contribution to the dose at these times after the shutdown is due to the permanent components. At different times this approximation cannot be considered still valid and the lifetimes of the components have to be taken into account to avoid excessive overestimations.

Separate simulations have been performed to calculate the dose along the axis of the horizontal port and KN3 survey. For the calculation along the mid port the KN3 geometry was not included in the geometrical model and global neutron and decay gamma generation and transport have been performed. The effect of the neutron backscatter from KN3 is negligible. For the KN3 front face survey the complete model was used but, in this case, the decay gamma generation was biased. As a matter of fact, at the time of the measurement, the camera was moved outside the torus hall. The measured doses correspond just to its activation induced by neutron during irradiation when it was located in front of the horizontal port. Then, in order to reproduce the experimental conditions, simulations of neutron transport on the whole MCNP model have been performed but the generation of decay gamma was only enabled in KN3.

3.2 MCNP MODEL OF JET OCTANT 1
The used 3-D MCNP 45° geometrical model of Octant 1 of JET is shown in figure 1. The main components can be identified in figure 1 (a). The vacuum vessel is made of a mixture of Inconel 600 and Inconel 625, the density of the mixture has been set according to the real weight. Port walls,

divertor and limiters' structures are in Inconel 600, plasma facing components are in carbon. The coils are made of copper, epoxy and water. The external shell of the mechanical structure is made of GGG NiMn 13-7 alloy. The outer TF and shell zone is described with a complex mixture of GGG NiMn 13-7, colemanite, polyethylene, copper, epoxy, SS-321 and water. The amount of the different materials has been chosen as to be consistent with real masses and volumes from reference [15]. Figure 1(b) shows the view of the model used for the calculation of the dose rate along the horizontal port and the positions of the detectors. The detectors have been simulated as void cylinders (radius 5 cm and thickness 10 cm). Considering the uncertainties on the experimental conditions, detailed modeling of the detectors' geometries was not justified. A front view of the KN3 system is shown in figure 1 (c). The collimator channels of the horizontal camera are embedded in a bulk shield made of high density concrete The shielding assembly cover is SS-316. The cylinders used to adjust collimators aperture are made of SS-304 L.

3.3 IRRADIATION HISTORY

The DD and DT irradiation scenarios used in FISPACT to calculate the decay gamma time correction factors are based on neutron yield data measured with conventional JET neutron diagnostic system. Fig. 3 shows the annual neutron yields for DD and DT components from 1983 to 2009. The DT component during operation with pure deuterium is due to triton-burn up (1.01MeV tritons are produced by D+D→p+t reaction) and it is of the order a few percent of the total. The DT peaks at 1991, 1997 and 2003 were corresponding to the tritium experiments performed at JET in the past. The total neutron yields during JET lifetime are 4.03×10^{20}, DD, and 2.4×10^{20} DT. The irradiation scenario used in FISPACT describe the whole JET history with an accurate representation of the period prior to shutdown. It should be noted that in the examined range of cooling times the dose rate is due to the activation during the last thirteen years of irradiation. The activation induced in the first decade of JET operations gives a negligible contribution. It has been verified that in the case of the upgraded KN3, installed at JET in 1995, the complete scenario can be used for the calculation of the dose rate at 95 days after shutdown without overestimation

4. COMPARISON BETWEEN CALCULATION AND MEASUREMENTS

Figure 3 shows the mesh map of the dose rate at 81 days after shutdown obtained with Advanced D1S method. The present visualization through the MCPLOT tally plotter of MCNP5 [8] allow to perform an interactive dose survey of the various zones inside and outside the vessel.

Figure 4 shows the radial profile of the calculated ambient dose equivalent rate at different times after shutdown. The statistical errors on the calculated doses are within a few percent. Experimental results are also shown for comparison. A very good agreement between calculation and measurements is obtained, except at 2m inside the port, maybe due to inadequate modelling of the surrounding structures.

However the time slope of calculated doses is steeper than the measurements. The differences

are more evident by examining the temporal profile of H*(10) shown in figure 5. The observed discrepancies can be attributed to an underestimation of the Co-60 and/or to an overestimation of the Co-58 contributions. The gammas generated from the Co-58 decay are the major contributors to the dose rate at 81 days after shutdown; conversely at longer cooling times the Co-60 decay is dominant. The Co-60 contribution is 30% at 81 days and 70% of the total dose at 263 days after shutdown. From the experimental point of view, the doses due to high energy gammas could be overestimated by the Teletector. As a matter of fact, the independent measurement performed with Eberline has shown a smoother time decrease with respect to Teletector, but steeper than calculated dose. Anyway, the available data are not sufficient to investigate further.

The calculated mesh maps of the dose rate in the front part of KN3 are shown in figure 6. The measured doses (Exp) presented at the end of the section 2.3 are also shown for comparison. The calculated dose pattern in the collimation zone follows the measured profile but the D1S calculation systematically underestimates the measurement. A maximum of ~3.3µSv/h was calculated on the right side of the central region close to the collimator #5. Maximum dose rate in upper collimator region was ~ 1.5µSv/h. Close to the lowermost collimator a maximum of ~ 2.2µSv/h was obtained. The dose rate was ≤0.7µSv/h at ± 25cm on the side of collimators and ≤0.2µSv/h at the lateral walls.The observed discrepancies between calculation and measurements can be due to material uncertainties, in particular on the bulk shield composition.

DISCUSSION AND CONCLUSIONS

A new benchmark performed as a preliminary experiment on the JET tokamak has been described. This preliminary survey, performed with dose meters routinely used for radiological protection purposes, confirms that the Advanced D1S with proper geometry and nuclear data reproduced well the measured quantities in the examined temporal range. With few exceptions, the D1S estimation of the doses along the port axis is within the error of the measurements. The KN3 activation is underestimated by a factor of 2 possibly due to uncertainties on materials modeling.

The results presented here are very satisfactory and the benchmark represents the first experiment so long after shutdown. However the accuracy of the measurements is too poor to quantify the C/E (Calculation over Experiment) ratio and uncertainty margin. More accurate measurements are needed. Crucial aspects for a future integral benchmark experiment are: proper detectors' selection and calibration, the necessity to measure both neutrons during irradiation and gammas at the shutdown to identify the radionuclides responsible to the dose. A higher level of accuracy in modelling and material impurities description is also necessary. This last issue is the key concern in the application to ITER and future machines since the quality of the prediction is mainly determined by approximations in the geometry and materials.

The Advanced D1S method will be applied to perform the shutdown dose rate calculation at JET with the new ITER-like wall. Drawbacks of D1S method exist: transport libraries have to be tailored to the specific problem and the method is still inadequate in treating multi-step reactions, but these

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limitations are not critical in the present applications. The direct coupling between the decay gamma and neutrons, the temporal dose behaviour and the dose mesh map in coupled neutronphoton transport of Advanced D1S represent main features in the application of this methodology in shutdown dose rate predictions.

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Date	12/01/2010	09/02/2010		09/03/2010		14/07/2010	
Time after shutdown (days)	81	109		137		263	
Detector Location	Teletector	Teletector	Mini Rad	Teletector	Mini Rad	Teletector	Mini Rad
1m from open port door	2	2	1.5	3	2		1
open port door	6	5	2	5	4		2
1m into port	13	11		10		6	
60cm into port			8		6		4.5
2m into port				69		39	
plasma centre	270	220		209		165	

Table 1: Mid-port measurements: Ambient dose equivalent rate (μSv/h)
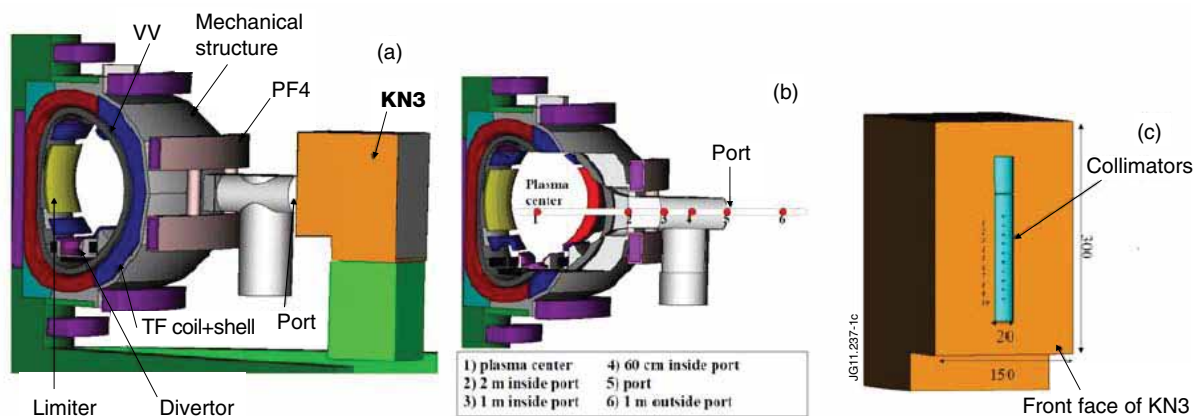

Figure 1: JET Octant 1 MCNP model: (a) global model with the main components pointed out: Vacuum Vessel (VV), Toroidal Field (TF) coil and shell, mechanical structure, limiter, divertor, Poloidal Field coil (PF) 4 and the KN3 system; (b)open view of the model used for mid port analysis, 1-6 are the positions of the detectors; (c) front view of the KN3 system, the collimators are numbered from 1 (uppermost) to 10 (lowermost).
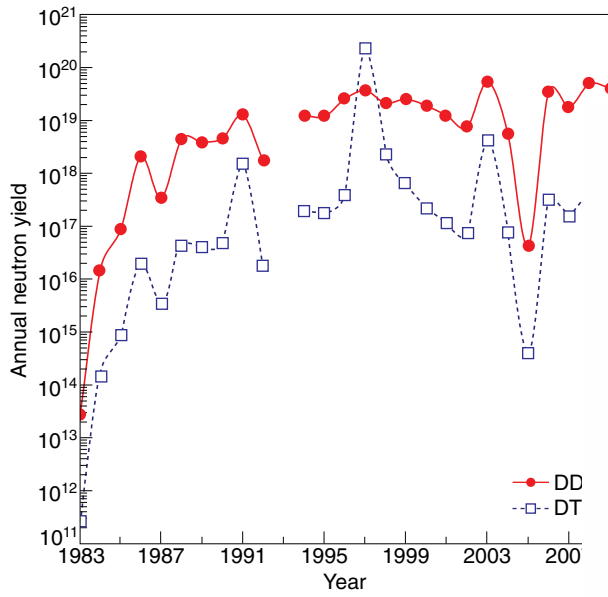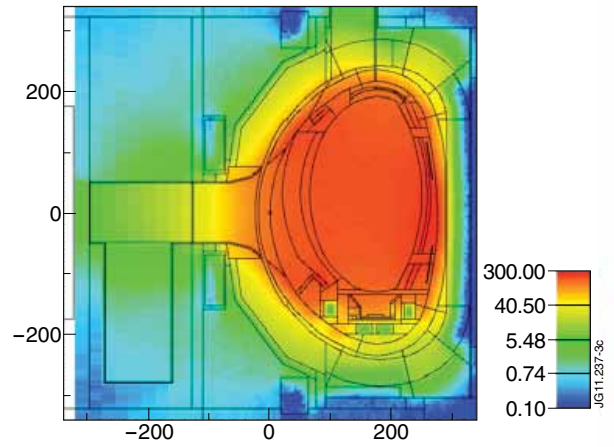
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Figure 2: Annual DD and DT neutron yields.

Figure 3: Calculated dose rate mesh map in μSv/hr at 81 days after shutdown superimposed over the middle radial-poloidal section of JET tokamak.

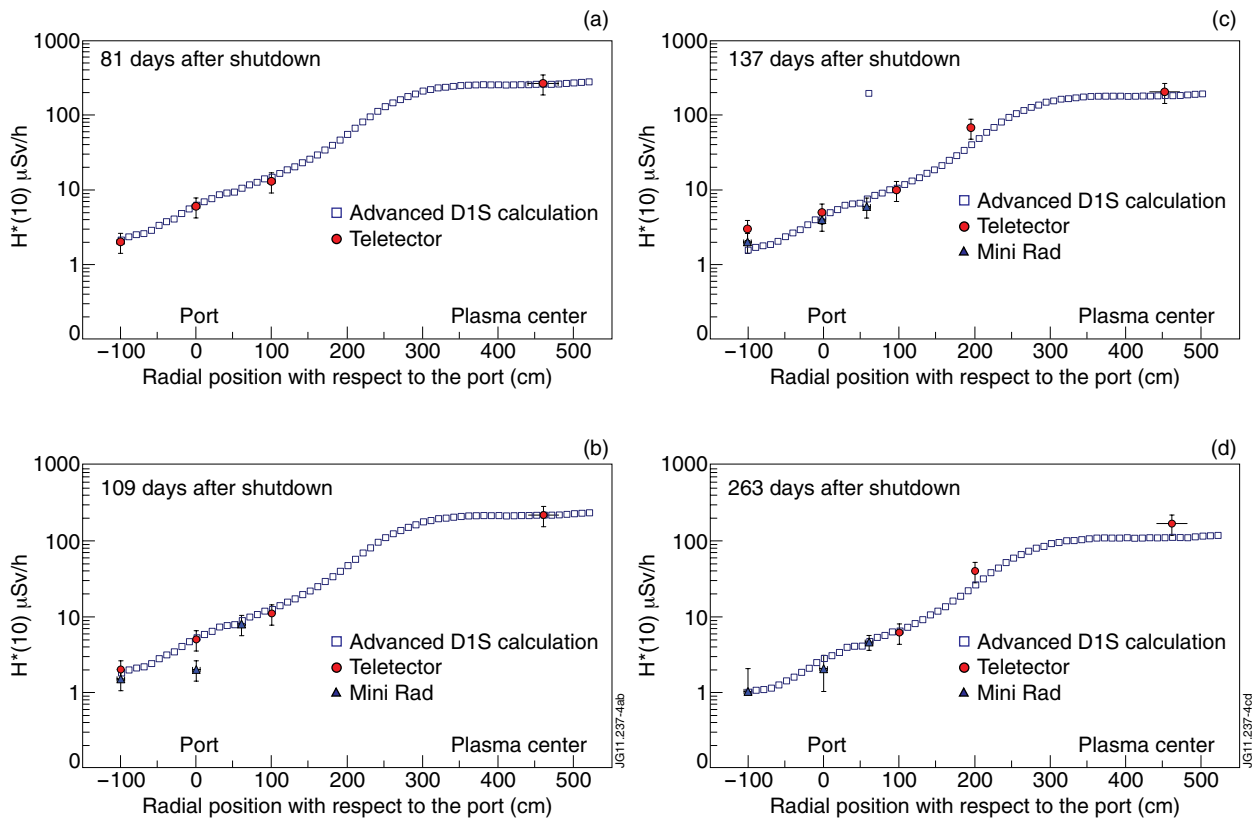*Figure 4: Radial profile of H*(10) rate calculated with Advanced D1S method and experimental data at different times after shutdown: 81 days (a), 109 days (b), 137 days (c) and 263 days (d). The reference radial position is the port door.*
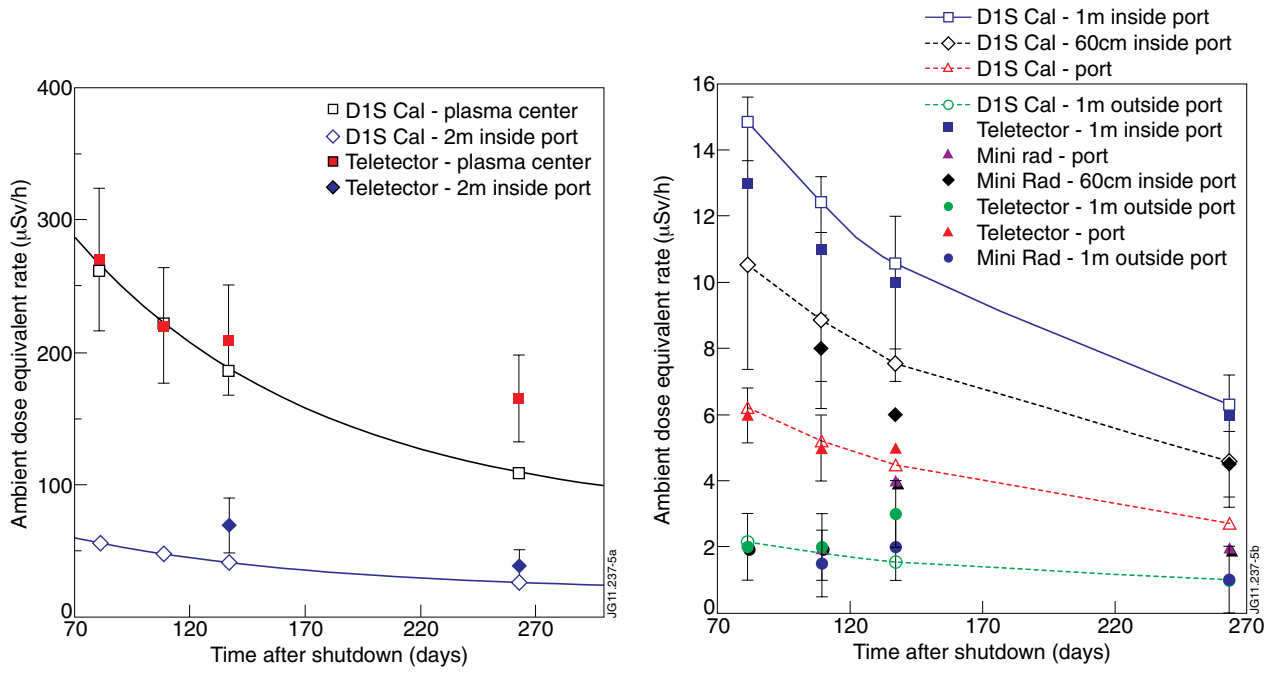
Figure 5: Temporal profile of H*(10) rate calculated with Advanced D1S method and experimental data at the plasma centre and at 2m inside port (top) and from 1m inside to 1m outside port (bottom).
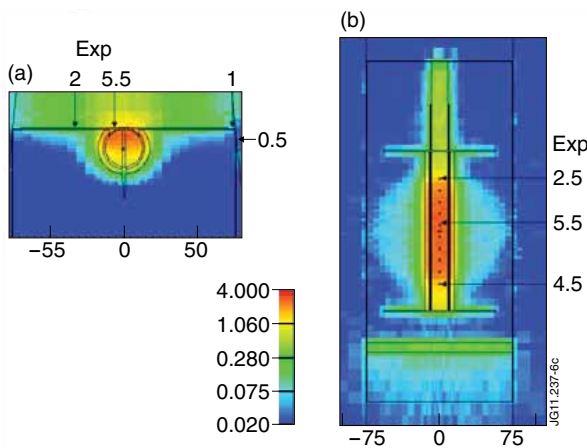

Figure 6: Calculated dose rate mesh map and measured doses (Exp) in μSv/hr of KN3 front zones at 95 days after shutdown: (a) collimator #5 toroidal-radial section; (b) toroidal-poloidal section (2 cm behind the front surface).