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Shutdown dose rate measurements with Ionization Chambers during and at the end of DT operations at JET

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Abstract

Within the framework of EUROfusion's technological exploitation of deuterium–tritium (DT) operation at JET—initiated under work package JET3 and continued under PrIO—the NEXP sub-project was conceived to exploit the substantial neutron yield expected during the DT campaigns (DTE2 and DTE3) to validate the numerical tools employed for neutron streaming and shutdown dose rate (SDDR) prediction in ITER. This validation, grounded in direct comparison between computational predictions and experimental measurements, constitutes a critical step in demonstrating the reliability of the SDDR methodology that underpins ITER's radiation safety case. As part of this activity, a dedicated dosimetry system based on spherical air-vented ionization chambers was installed in the JET Torus Hall in 2015 and has since undergone successive hardware and software upgrades to address operational challenges identified across DT experimental campaigns. This work traces the evolution of the SDDR dosimetry system and presents the analysis of the measurements acquired during the DT operation of JET, in particular the third DT campaign (DTE3) and, uniquely, throughout the ongoing final shutdown, a phase offering measurement conditions unlikely to be replicated elsewhere. SDDR predictions with the Advanced D1S tool by ENEA are described as well.

1. Introduction

Reliable prediction of the shutdown dose rate (SDDR) generated by neutron-activated materials is a safety-critical requirement for the design, licensing and hands-on maintenance planning of ITER. The EUROfusion work package WP JET3 [1], and subsequently WP PrIO (Preparation of ITER Operations) [2], within the NEXP (Neutronics Experiments) sub-project [3–5], was set up to exploit the exceptional 14-MeV neutron production of the JET deuterium–tritium campaigns (DTE2, 2021, and DTE3, 2023) [6,7] to test and validate the numerical tools used for SDDR assessment against high-quality experimental data obtained under conditions directly relevant to ITER. A dosimetry system based on ionization chambers (ICs), operated in the JET Torus Hall and progressively upgraded since 2015 through the preceding deuterium–deuterium (DD) and tritium–tritium (TT) campaigns, provided continuous air-kerma-rate measurements throughout DTE2, DTE3, and the final shutdown. Two 1-liter spherical air-vented ICs were positioned close to the horizontal ports of Octants 1 and 2, complemented by a third, less sensitive chamber added in Octant 1 to accommodate the higher dose-rate levels expected during DTE2.

The importance of producing a strong dataset on SDDR data across the most relevant campaigns of JET is due to the fact that SDDR is a licensing-relevant quantity: it directly governs how, when and

Table 1. JET campaigns since 2016 across which the SDDR dataset was produced. The deuterium–tritium campaigns DTE2 (C41) and DTE3 (C46) are shown in bold. Neutron yields are calculated from the JET neutron monitor KN1 data.

JET campaign	Start date	End date	Total N yield	Max N yield per pulse
C36a (DD)	4 January 2016	27 June 2016	7.63×10^{18}	5.01×10^{16}
C36b (DD)	10 October 2016	15 November 2016	1.13×10^{19}	1.26×10^{17}
C38a (DD)	3 June 2019	20 December 2019	3.69×10^{19}	1.47×10^{17}
C38b (DD)	17 February 2020	23 March 2020	1.49×10^{19}	2.14×10^{17}
C38c (DD)	6 July 2020	26 September 2020	1.66×10^{19}	1.92×10^{17}
C39T (TT)	7 December 2020	18 December 2020	6.08×10^{15}	1.60×10^{15}
C40 (TT)	4 January 2021	31 July 2021	8.52×10^{18}	1.46×10^{17}
C41 (DT, a.k.a. DTE2)	8 August 2021	21 December 2021	8.48×10^{20}	2.09×10^{19}
C40 (T-Post DT)	17 January 2022	4 March 2022	2.48×10^{18}	2.13×10^{17}
C42 (D—T removal)	7 March 2022	26 August 2022	8.25×10^{18}	1.80×10^{17}
C43 (Helium)	1 September 2022	7 November 2022	9.74×10^{14}	3.46×10^{14}
C44 (Deuterium)	8 November 2022	16 December 2022	4.02×10^{18}	1.01×10^{17}
C45 (Deuterium)	27 February 2023	12 August 2023	2.90×10^{19}	1.83×10^{17}
C46 (DT, a.k.a. DTE3)	21 August 2023	14 October 2023	7.31×10^{20}	2.46×10^{19}
C47 (Cleaning)	16 October 2023	24 November 2023	2.17×10^{19}	2.37×10^{17}
C45b (DD)	25 November 2023	20 December 2023	3.00×10^{17}	1.53×10^{16}

for how long personnel can safely access ITER cells and interspaces after operation, and inaccuracies in SDDR predictions translate directly into higher maintenance-schedule and dose-budget margins. Moreover, DTE2 and DTE3 are, to date, the closest experimental analogs to ITER neutronics available on any operating tokamak, with a 14-MeV neutron yield of about 8.5×10^{20} and 7.3×10^{20} neutrons, respectively (orders of magnitude above the preceding DD/TT campaigns), making them a uniquely valuable and largely irreplaceable validation dataset. Furthermore, the measured dose-rate ranges at JET (about $100 \mu\text{Gy h}^{-1}$ – 10 mGy h^{-1} in Octant 1 and $5 \mu\text{Gy h}^{-1}$ – $600+ \mu\text{Gy h}^{-1}$ in Octant 2 during DTE2) fall squarely within the levels expected in ITER port cells and interspaces, giving the comparison direct programmatic relevance rather than being a mere scaled-down analogy. A fourth point to support the importance of the SDDR dataset lies in the rigorous and protocol-based uncertainty budget presented, which turns the dataset into a quantitative benchmark, thus enabling meaningful discrimination between nuclear models, SDDR tools, candidate nuclear data libraries and tokamak scenario assumptions.

Table 1 covers the full sequence of JET experimental campaigns from 2016 through late 2023, comprising the earlier DD campaigns (C36a, C36b, C38a–c), the TT campaigns (C39T, C40), the deuterium–tritium campaigns DTE2 (C41) and DTE3 (C46), and the various post-campaign operations in between and after them (T-Post DT, D–T removal, Helium, cleaning, and additional Deuterium campaigns C44, C45, C45b). As before, the non-DT campaigns are characterized by comparatively modest neutron production, with total yields ranging from about 10^{15} – 10^{19} , reflecting their role in low-power fusion operation, machine conditioning, instrument testing, and preparatory benchmarking. DTE2 (August–December 2021) and DTE3 (August–October 2023) stand out as the two dominant campaigns in the dataset, each producing a total 14-MeV neutron yield roughly two orders of magnitude above any other campaign: 8.5×10^{20} for DTE2 and 7.3×10^{20} for DTE3, with maximum per-pulse yields of 2.09×10^{19} and 2.46×10^{19} , respectively—the latter representing the highest single-pulse yield recorded across the whole campaign history. Together, these two DT campaigns bookend the extended dataset and provide the only two opportunities within this timeframe to generate ITER-relevant neutron fluxes and SDDR conditions of sufficient intensity to rigorously validate nuclear analysis tools.

The present work is focused on the SDDR measurements at JET during the DT campaigns, with a focus on the DTE3 and surrounding campaigns, and during the final shutdown. The evolution of the measurement system is first retraced across the main steps that occurred since the preparation for the first installation at JET in 2015. Subsequently, the characterization of the influence quantities and error sources affecting the IC readings, from which the correction procedures applied to determine accurate dose rate values are derived, is described. The resulting SDDR data is then presented, with major emphasis on DTE3 and final shutdown, together with the experimental points selected for benchmarking of SDDR tools based on neutron transport and activation codes. Finally, the SDDR calculations with the ENEA tool Advanced D1S [8,9] and comparison against experimental points are presented. Some final implications of these results for ITER are discussed as concluding remarks.

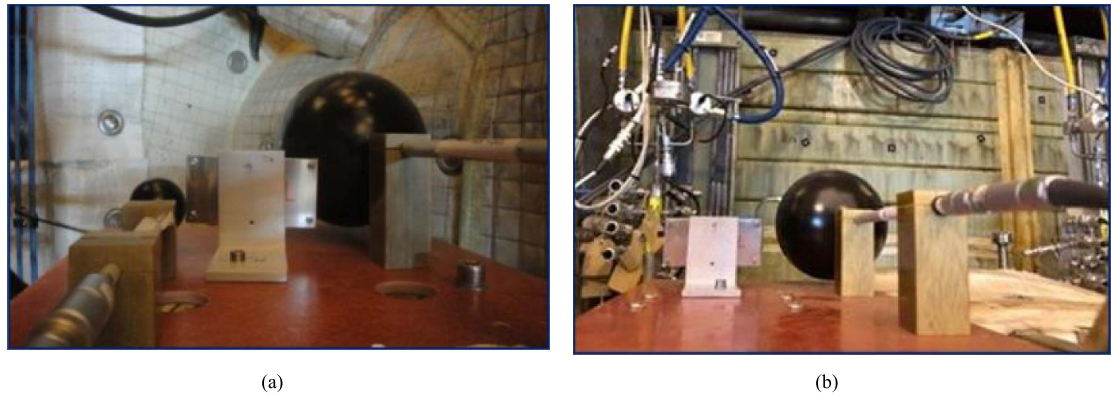


Figure 1. Views of the installation of ICs on proper shelves in Octant 1 (a) and Octant 2 (b).

2. Experimental equipment

The measurement equipment for the SDDR experiment consisted of three active dosimeters calibrated for air kerma. The preparation of the system, installation and upgrades can be found in detail in [10–15] and are recalled here for the sake of providing the full picture across the JET campaigns. Each dosimeter was built around an air-vented spherical IC: two of the ICs have a 140 mm diameter and a sensitive volume of 1000 cm³, PTW model 320 023 [16]. They were installed at JET, ex-vessel, on a side port in Octant 1, near the Radial Neutron Camera (dubbed ‘IC-Oct1-big’), and on top of the ITER-like Antenna in Octant 2 (dubbed ‘IC-Oct2-big’). The third IC is smaller, with a 44 mm diameter and a 30 cm³ sensitive volume and is a PTW model 320 055 (‘IC-Oct1-small’). Located on the same shelf as the ‘IC-Oct1-big’ in Octant 1, this smaller detector was better suited for the higher dose rates anticipated during DTE2, as its response was approximately 1/40th of that of the larger ICs. In figure 1 the three ICs installed in Octants 1 and 2 are shown.

These ICs were chosen for their excellent reproducibility, long-term stability, and flat energy response in terms of air kerma, a crucial feature given the complex gamma radiation field at JET. Their spherical design ensures a nearly uniform response to gamma radiation from all directions. The ICs operate in current mode and the signal, i.e. the ionization current generated by the interaction of air with the gamma radiation field, is analyzed by three electrometers, one for each dosimeter. The electrometers (PTW, model UNIDOS) are located in the cubicles’ hall (J1D) and are connected to a computer via an Ethernet interface, cf figure 2(a). Long triaxial cables (approximately 100 meters) connect the ICs in the Torus Hall (J1T) to the electrometers, designed for precise current measurements and low leakage from irradiation. These cables also supply the high voltage (400 V) to the ICs. The IC signal is integrated over a set integration time—30 s during plasma campaigns and a longer interval during shutdown periods—to obtain the collected charge, which is then converted into air-kerma rate through calibration factors and corrected for deviations from calibration conditions and for relevant influence quantities, including the reduction of oxygen concentration in the Torus Hall air during tritium operations.

A software application developed by ENEA controls the measurement assembly and data acquisition from a PC in J1D. The software enables remote control of electrometers, manages data handling and storage, and provides instrument readings and communication information. The collected data is backed up daily to a JET server named catserver. The system is also remotely manageable via network tunneling. Data sharing with the JET control and data acquisition system (CODAS) is managed by a separate software scheme, cf figure 2(b). Three software instances (IC1.exe, IC2.exe, IC3.exe) run, one for each detector, while a fourth program (codas.exe) writes the dose rate data to an exchange file that is accessed by a JET CODAS application (JetFsmExt.exe) that allows external software to interact with the system. Real-time copies of SDDR data are sent to CODAS via HTTP and stored in the Continuous Data Recording System (CGRT) on a Solaris server. A dedicated virtual instrument display, or mimic, is also available for real-time readings, cf figure 2(b).

2.1. Pre-installation tests and calibration

The active dosimetry systems deployed for the SDDR experiment were characterized prior to installation through calibration in terms of air kerma, carried out at the ENEA-INMRI gamma calibration laboratory [17] and at the manufacturer’s laboratory, see table 2. Both ICs then installed in Octant 1

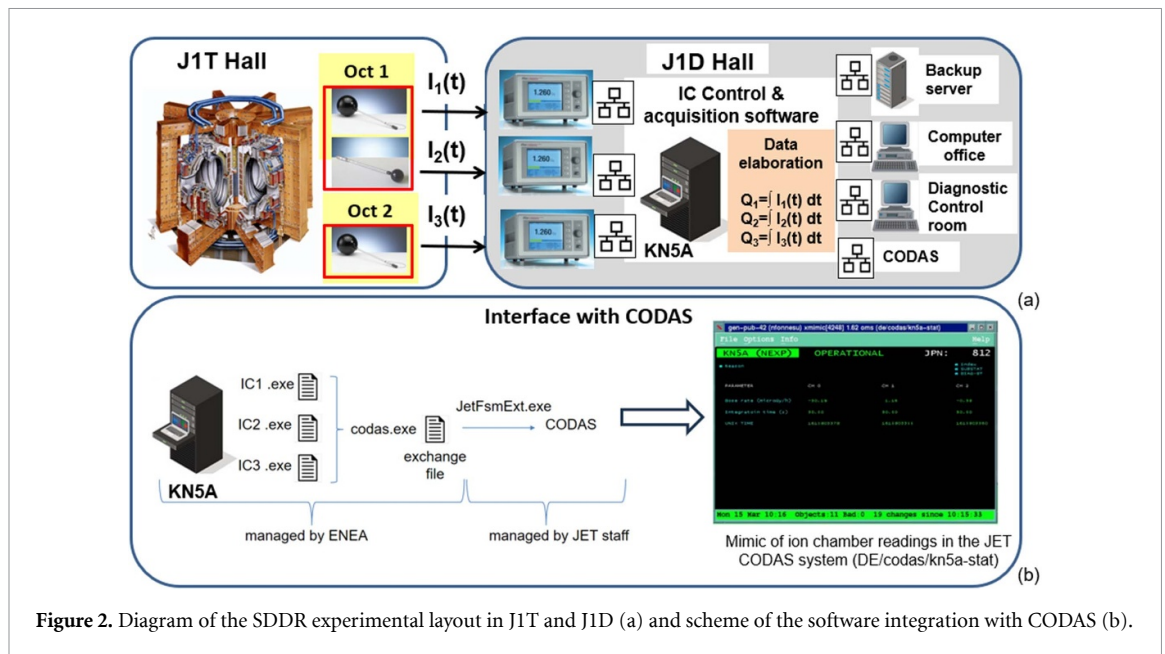


Figure 2. Diagram of the SDDR experimental layout in J1T and J1D (a) and scheme of the software integration with CODAS (b).

Table 2. Radiation qualities employed for the calibration of ICs and calibration factors.

IC	Radiation quality	N_{kair} (Gy/C)
IC-Oct1-small	X-ray (40/150/300 keV); Am; Cs; Co	1.112×10^6 (U = 3.73%)
IC-Oct1-big	X-ray (40/150/300 keV); Am; Cs; Co	2.451×10^4 (U = 4.08%)
IC-Oct2-big	Co (1253 keV)	2.504×10^4 (U = 2.50%)

(IC-Oct1-big and IC-Oct1-small) were exposed to a set of x-ray and gamma reference beam qualities at INMRI spanning approximately 30 keV to 1.3 MeV, following the ISO 4037 standard [18], using INMRI's national standard reference chambers to establish the air kerma at the reference point. The PTW laboratory provided calibration only with cobalt for all three dosimeters. For each dosimetry system, an air kerma calibration factor was derived at each beam quality as the ratio of the reference air kerma to the instrument reading, and an equivalent, energy-averaged calibration factor was subsequently obtained as the weighted least-squares estimator over all calibration points, with the associated uncertainty calculated from the sample variance [10]. This procedure confirmed that both chamber types exhibit a flat energy response in terms of air kerma, with a maximum spread of 4.1% across the calibrated energy range—a property that is essential given that the gamma energy spectrum arising from neutron-activation decay at the detector position varies over time and cannot be matched to a single calibration quality. A cross-calibration between 'IC-Oct1-big' and 'IC-Oct2-big' dosimetry systems, performed with three Cs-137 reference sources at dose rates between 0.2 and 3.6 mGy h⁻¹, showed the two systems to agree to within 1%, with a small systematic overestimation of about 0.5% by the 'IC-Oct2-big.' The response of the ICs under neutron irradiation, and their susceptibility to self-activation, was assessed through dedicated tests at the Frascati neutron generator (FNG) [19]. A first test confirmed that, following a run of 14 MeV neutron irradiation, the dosimetry system correctly reproduced the background dose rate in the laboratory once the neutron source was switched off.

A subsequent test irradiated an IC at a fixed distance from the FNG target for approximately three hours, corresponding to a neutron fluence at the detector position of the order of 10⁸ cm⁻². Following irradiation, the chamber was relocated to a low-background control room and monitored continuously; an exponential decay of the measured air kerma rate was observed, with a decay constant corresponding to a half-life of approximately 0.9 h, consistent with short-lived activation of the air enclosed within the chamber volume rather than activation of the chamber's structural materials. Comparison with a second, non-irradiated chamber of identical design confirmed that, after approximately 24 h, the two systems yielded statistically indistinguishable readings, indicating no residual signal attributable to self-activation and no measurable radiation damage to the detector.

2.2. Preparation of the T phase

The JET3/NEXP shutdown-dose-rate program has been refining its measurement setup since the DD campaigns of 2016, using lessons from each successive campaign. The first setup installed was based on the two big ICs, in Octants 1 and 2. With the 2021 deuterium–tritium campaign (DTE2) expected to produce a substantially higher 14-MeV neutron yield than anything measured before, the tritium-only (TT) campaign was used as a proving ground—testing upgraded hardware and software under realistic conditions before the higher-intensity DTE2 run. The hardware upgrade consisted of the installation of the third, smaller chamber (44 mm diameter) in Octant 1 [13,14]. Being intrinsically less sensitive, it can keep measuring accurately at dose-rate levels that would saturate or exceed the range of the two larger chambers—effectively extending the system’s dynamic range upward in anticipation of DTE2’s stronger radiation field.

A less obvious but important preparatory step concerned the atmosphere itself. During tritium operations, JET reduces the oxygen content of the Torus Hall air (replacing it with nitrogen) as a fire-suppression precaution. Since these ICs are air-vented—meaning the surrounding air is literally their detection medium—this raised the problem of characterizing their response as the air composition changes. A spare chamber, of the same model as the big ICs, was tested in a controlled laboratory setup, where the oxygen fraction inside a sealed enclosure could be adjusted gradually while gamma sources of known intensity irradiated the chamber [13,14]. This revealed a measurable dependence of the chamber response on oxygen concentration, and an additional uncertainty term (up to 1.4%, depending on dose rate), incorporated into the overall measurement uncertainty budget, was quantified for operation in the reduced-oxygen atmosphere used during tritium campaigns. The same spare chamber was then installed in Octant 2 to replace the previous one, in which a fault was discovered after a pre-campaign calibration check (traced to a probable short circuit in a cable connector).

While the SDDR dataset of DTE2 is based on the three dosimeters, the small IC in Octant 1 was disconnected before DTE3 in the middle of 2023 as its readout electronics were required for the Water Activation Experiment (WACT) [5] within the same WP PrIO.

3. Experimental uncertainty and correction of instrument readings

The chambers’ ionization current, once corrected for the background/leakage current, is integrated over a chosen time window to obtain the collected charge for that interval. During the campaign this window was 30 s, long enough to give stable statistics; during longer shutdown periods it can be stretched to 600 s. Charge collected per unit time is converted to air kerma rate by multiplying by the chamber’s calibration factor (obtained at the ENEA-INMRI metrology lab) and a beam-quality correction, after first applying a set of corrections for conditions that differ from the calibration environment. A thorough description is given in [14], while in the following, a short description of the correction terms applied to the raw reading is provided.

- Air density (temperature and pressure). Because the chambers are open to the atmosphere, the mass of air inside them, and hence the charge collected, depends on ambient density. A correction derived from the ideal gas law compares standard calibration conditions (293.15 K, 1013 hPa) to the conditions during measurement. Temperature is inferred from the ventilation system’s reading plus a 5 K offset to account for the chambers’ proximity to the roughly 300 °C in-vessel components, giving an estimated uncertainty of 1.7%. Pressure is taken from a gauge near the neutral-beam injector high-voltage tower in Octant 8, with an estimated uncertainty of 1.0%. Both quantities are logged continuously and interpolated to the measurement times; the overall density correction stays within about 10%.
- Humidity. Although humidity affects several underlying physical mechanisms, these largely cancel out, leaving a residual reading error quantified as $\pm 0.15\%$ across the 20%–80% relative-humidity range; no explicit correction is applied, only this uncertainty allowance. Relative humidity itself is derived from the dewpoint.
- Ion recombination. A small fraction of the charge is lost to recombination before collection. Because the calibration factor already incorporates this loss, the same correction is carried through to the field measurements; its magnitude (about 0.1%–0.2%) is small enough that the associated uncertainty is dropped from the budget.

Table 3. Uncertainty budget for the three ionization chambers during DT operation. Values that differ by chamber are listed in the order IC-Oct1-small/IC-Oct1-big/IC-Oct2-big. The last row (in bold) gives the combined relative standard uncertainty ($k = 1$), obtained by summing the individual contributions in quadrature [14].

Source of uncertainty	Factor	Exp. unc. (%)	PDF	Conf. %	Cov. factor	$u(x_i)/x_i$ (%)
Temperature	k_{TP}	1.70	Rect	100	1.73	0.98
Pressure	k_{TP}	1.00	Rect	100	1.73	0.58
Humidity	k_h	0.15	Rect	100	1.73	0.09
Ion recombination	k_{sat}	Neglected	—	—	—	—
Stability (IC)	k_{stab}	1.00	Rect	100	1.73	0.58
Stability (electrometer)	k_{stab}	0.10	Rect	100	1.73	0.06
Linearity	k_{lin}	0.25	Rect	100	1.73	0.14
Leakage current	k_{leak}	Neglected	—	—	—	—
Tilting	k_{rot}	3.00/5.00/5.00	Rect	100	1.73	1.73/2.89/2.89
Rotation	k_{rot}	0.50	Rect	100	1.73	0.29
Oxygen	k_{oxygen}	1.40	Rect	100	1.73	0.81
Resolution	—	0.50	Rect	100	1.73	0.29
Repeatability	—	0.25	Norm	68	1.00	0.25
Energy dependency	—	—/—/4.00	Rect	100	1.73	—/—/2.31
Calibration factor	N_{kcal}	3.73/4.08/2.50	Norm	95	2.00	1.87/2.04/1.25
Experimental uncertainty				66/64/66	1.00	3.0/3.9/4.2

- Long-term stability. Repeat checks suggest the chambers' response can drift by $\pm 1\%$ and the electrometers by $\pm 0.1\%$ over time; no correction is applied, but these figures are kept as uncertainty contributions.
- Linearity. The manufacturer specifies a worst-case linearity error of $\pm 0.25\%$, carried as an uncertainty with no correction applied.
- Leakage current. Since background/leakage current is already subtracted from the raw signal under the assumption that it stays constant, no further correction or uncertainty is needed here.
- Field geometry (tilt and rotation). Calibration assumes a beam perpendicular to the chamber's axis, but the real radiation field in the Torus Hall arrives from many directions at once. Deriving proper geometric correction for that would be very difficult, so none is applied; instead, the manufacturer's angular-response figures under tilt ($\pm 3\%$ for IC-Oct1-small and $\pm 5\%$ for IC-Oct1-big/IC-Oct2-big) and $\pm 0.5\%$ for rotation are carried as uncertainties.

Because air kerma rate is expressed as a product of independent factors [11], the overall relative uncertainty is obtained by summing the individual relative uncertainties in quadrature (root-sum-of-squares), following ISO guidance. Table 3 lists every contributing term together with its assumed probability distribution; values that differ between chambers are given in the order IC-Oct1-small/IC-Oct1-big/IC-Oct2-big. Note that IC-Oct2-big, unlike the other two chambers, was calibrated by the manufacturer at a single radiation quality (Co-60), so its energy-dependence uncertainty (4%, from the manual) is added separately, whereas IC-Oct1-small and IC-Oct1-big had their energy response characterized directly during calibration at several radiation qualities. Regarding repeatability, the value adopted in this analysis is taken from the instrument manual and is applied whenever only a single measurement point is available. For the SDDR measurements reported in the following, the uncertainty associated with repeatability is instead evaluated as the standard deviation of the measurement points acquired around the selected cooling time, within a sufficiently short time interval.

Putting all contributions together, the combined relative standard uncertainty in air kerma rate (1-sigma) for DTE2 and DTE3 works out to 3.0% for IC-Oct1-small, 3.9% for IC-Oct1-big, and 4.2% for IC-Oct2-big; the overall distribution was assessed as approximately Gaussian with confidence levels of 66%, 64% and 66%, respectively [11].

4. SDDR across DTE3 and benchmark point selection

While DTE2 was covered in earlier publications [14], this section focuses on SDDR measurements over the full 2023 operational year, encompassing above all the DTE3 campaign, but also the earlier DD campaign C45 and the subsequent clean-up/contingency campaign C47, and the first year of JET

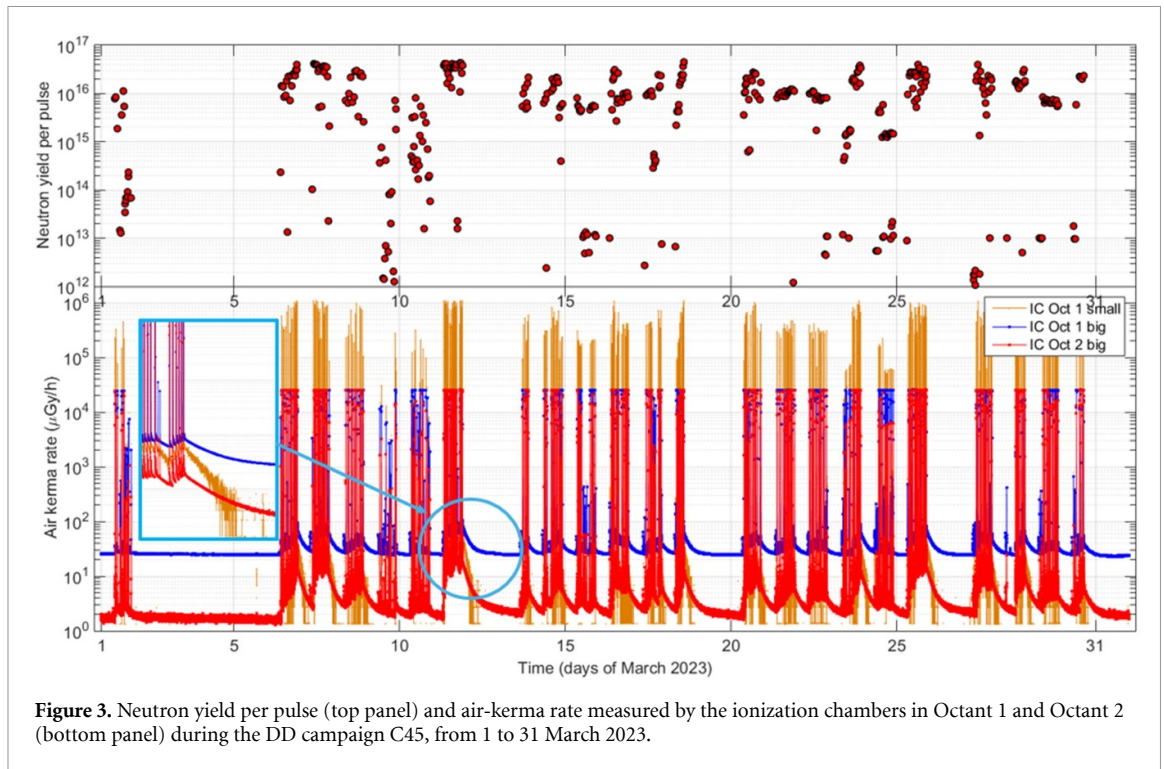


Figure 3. Neutron yield per pulse (top panel) and air-kerma rate measured by the ionization chambers in Octant 1 and Octant 2 (bottom panel) during the DD campaign C45, from 1 to 31 March 2023.

shutdown (January–December 2024). Particular emphasis is placed on the construction of the SDDR DTE3 benchmark input package used to validate Rigorous-2-Step (R2S) and Direct-1-Step (D1S) SDDR tools [5], based on Monte Carlo transport codes (MCNP [20], TRIPOLI-4 [21], OpenMC [22]) against the DTE3 experimental campaign, including the irradiation histories for neutron activation calculations.

4.1. January 2023 shutdown and DD campaign C45

During the shutdown preceding the start of the DD campaign C45, the dose rate in Octant 1 decreased from approximately $35 \mu\text{Gy h}^{-1}$ at the beginning of January 2023 to approximately $20 \mu\text{Gy h}^{-1}$ at the end of February, reflecting the ongoing radioactive decay of the activation products accumulated during the preceding operations. During campaign C45 (see figure 3), the dose rate level varied in the range of approximately $20\text{--}100 \mu\text{Gy h}^{-1}$ in Octant 1 and of approximately $1.5\text{--}10 \mu\text{Gy h}^{-1}$ in Octant 2, tracking the activation due to the pulse-by-pulse neutron production of the DD operations. Noteworthy, the quick decrease of IC-Oct1-small signal below the measuring range, suddenly after JET pulses of the second week of March 2023, is visible in the magnified inset panel in figure 3 and is representative of the response of such instrument to less intense campaigns. The peaks visible in the air-kerma rate trace correspond to the neutron emission of individual JET pulses; during those intervals the IC signal does not represent a genuine dose-rate measurement, since it exceeds the upper limit of the instrument's measuring range and the chambers are, in any case, not calibrated for operation under a direct neutron field.

4.2. Transition to DTE3 (August 2023)

As DD operations progressed into the early stage of the DTE3 tritium campaign, the dose rate levels in both octants increased markedly, reflecting the higher-yield DT pulses being introduced. The dose rate measured in Octant 1 remained systematically higher than in Octant 2, because the Octant 2 detector is located in a more heavily shielded position; consistently, the gamma decay observed in Octant 2 was faster than in Octant 1, as anticipated by earlier pre-analysis studies. The boxed interval in figure 4 identifies the subset of measurements selected for the DTE3 benchmark exercise (irradiation history IH#1).

4.3. DTE3 campaign (September 2023)

Through the core of the DTE3 campaign the SDDR level increased substantially in both octants, reaching the range from approximately $30 \mu\text{Gy h}^{-1}$ to approximately 20 mGy h^{-1} in Octant 1 and from approximately $3 \mu\text{Gy h}^{-1}$ to approximately 5 mGy h^{-1} in Octant 2, a range comparable to that already observed during DTE2, cf. figure 5.

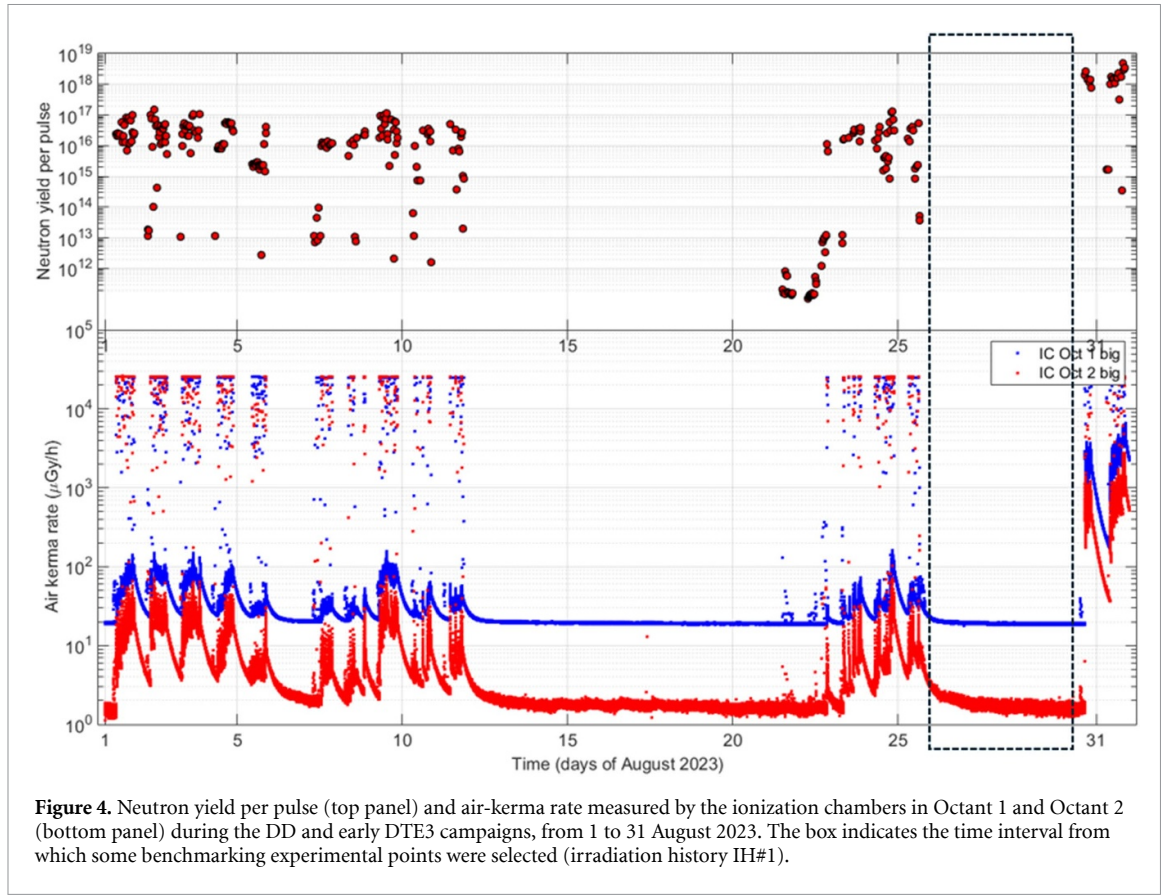


Figure 4. Neutron yield per pulse (top panel) and air-kerma rate measured by the ionization chambers in Octant 1 and Octant 2 (bottom panel) during the DD and early DTE3 campaigns, from 1 to 31 August 2023. The box indicates the time interval from which some benchmarking experimental points were selected (irradiation history IH#1).

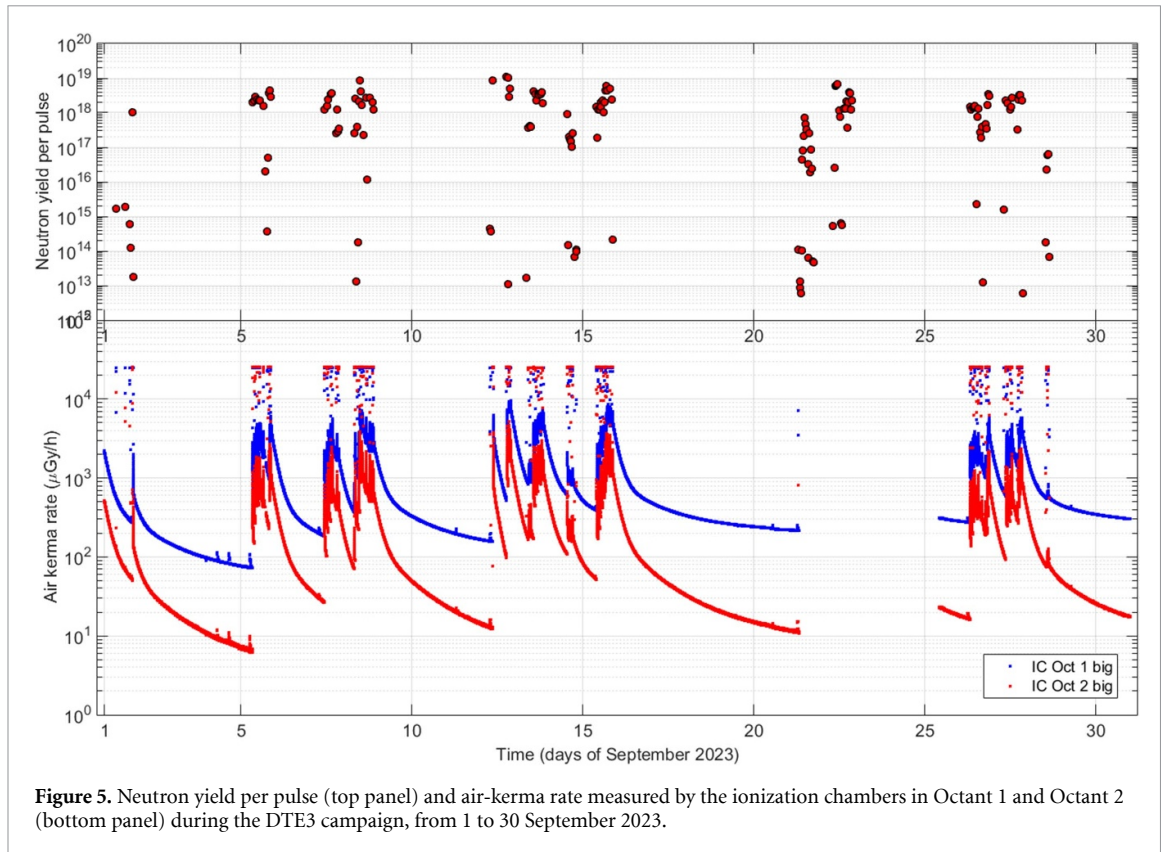


Figure 5. Neutron yield per pulse (top panel) and air-kerma rate measured by the ionization chambers in Octant 1 and Octant 2 (bottom panel) during the DTE3 campaign, from 1 to 30 September 2023.

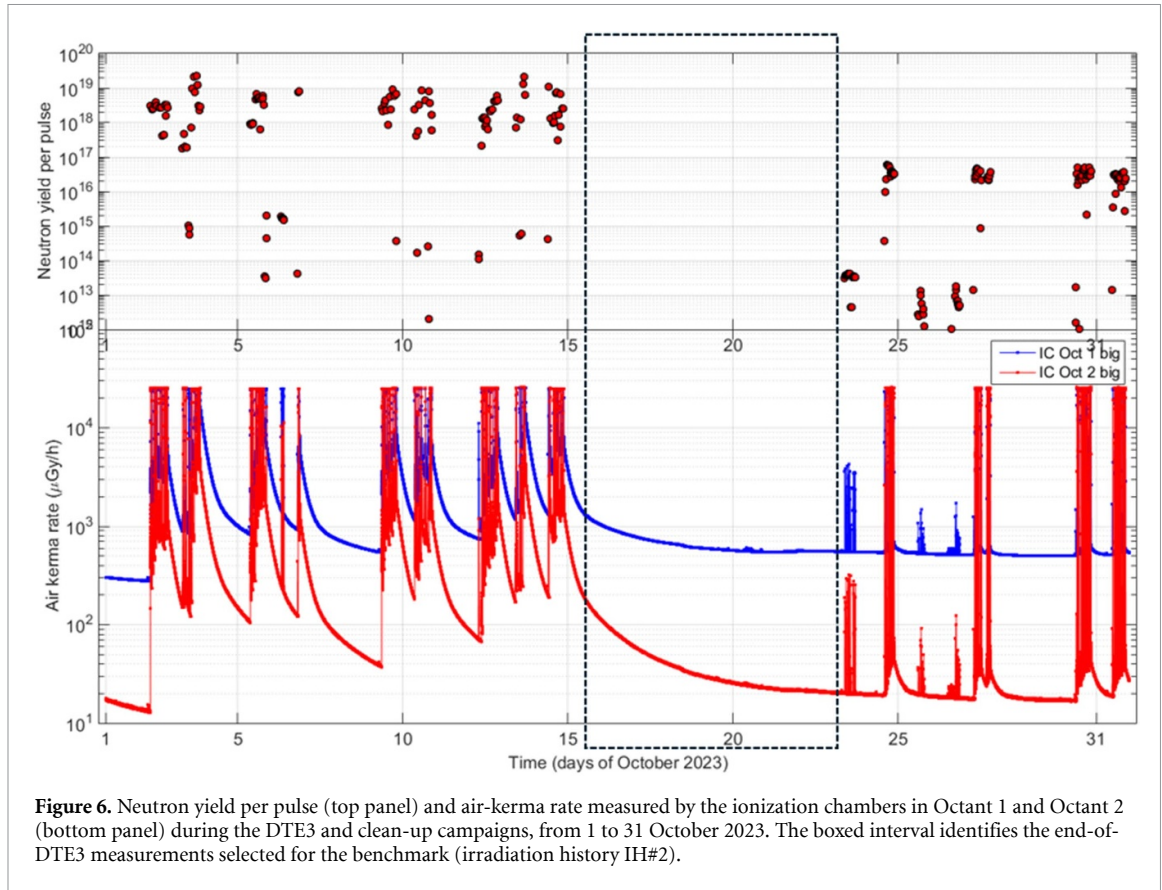


Figure 6. Neutron yield per pulse (top panel) and air-kerma rate measured by the ionization chambers in Octant 1 and Octant 2 (bottom panel) during the DTE3 and clean-up campaigns, from 1 to 31 October 2023. The boxed interval identifies the end-of-DTE3 measurements selected for the benchmark (irradiation history IH#2).

4.4. DTE3 and clean-up transition (October 2023)

The clean-up campaign C47 began in the second part of October 2023, following the completion of DTE3 tritium operations. Several high-power pulses completed the DTE3 campaign, as is visible in figure 6, upper plot, with several dots exceeding 10^{19} neutrons produced per pulse. During the transition, the SDDR remained at the elevated levels reached at the end of DTE3. The boxed interval in figure 6 marks the measurements selected as the end-of-DTE3 reference point for the benchmark input package (irradiation history IH#2).

4.5. Clean-up and contingency campaign C47 (November–December 2023)

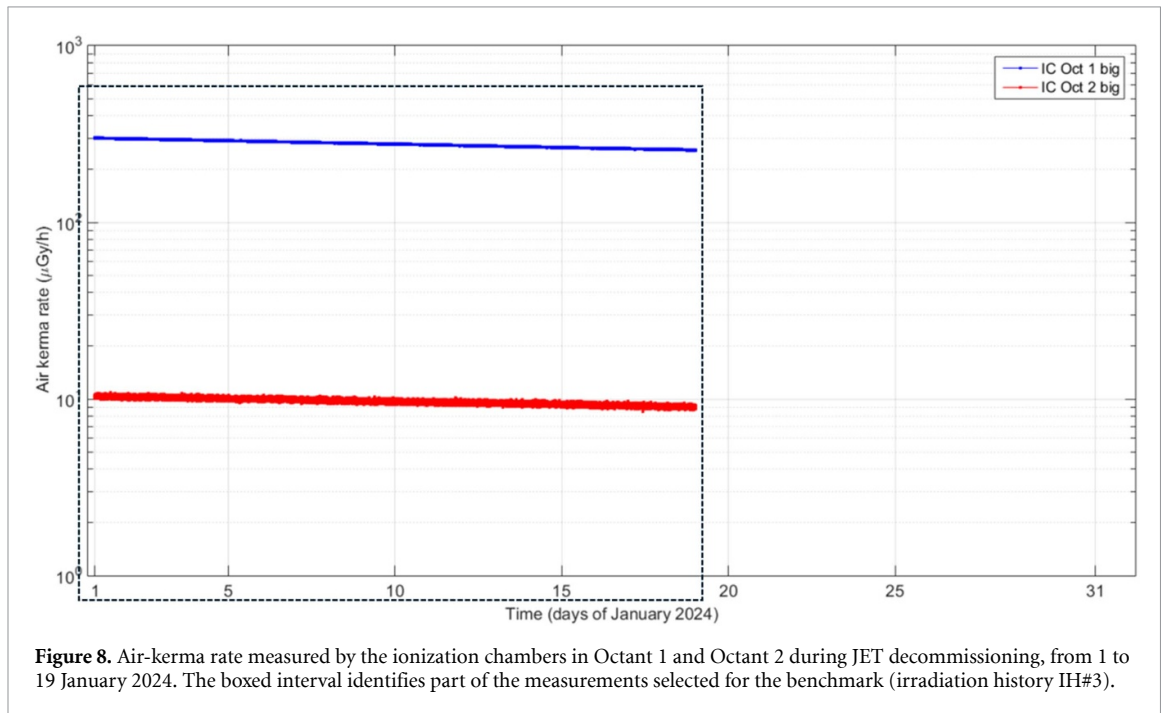
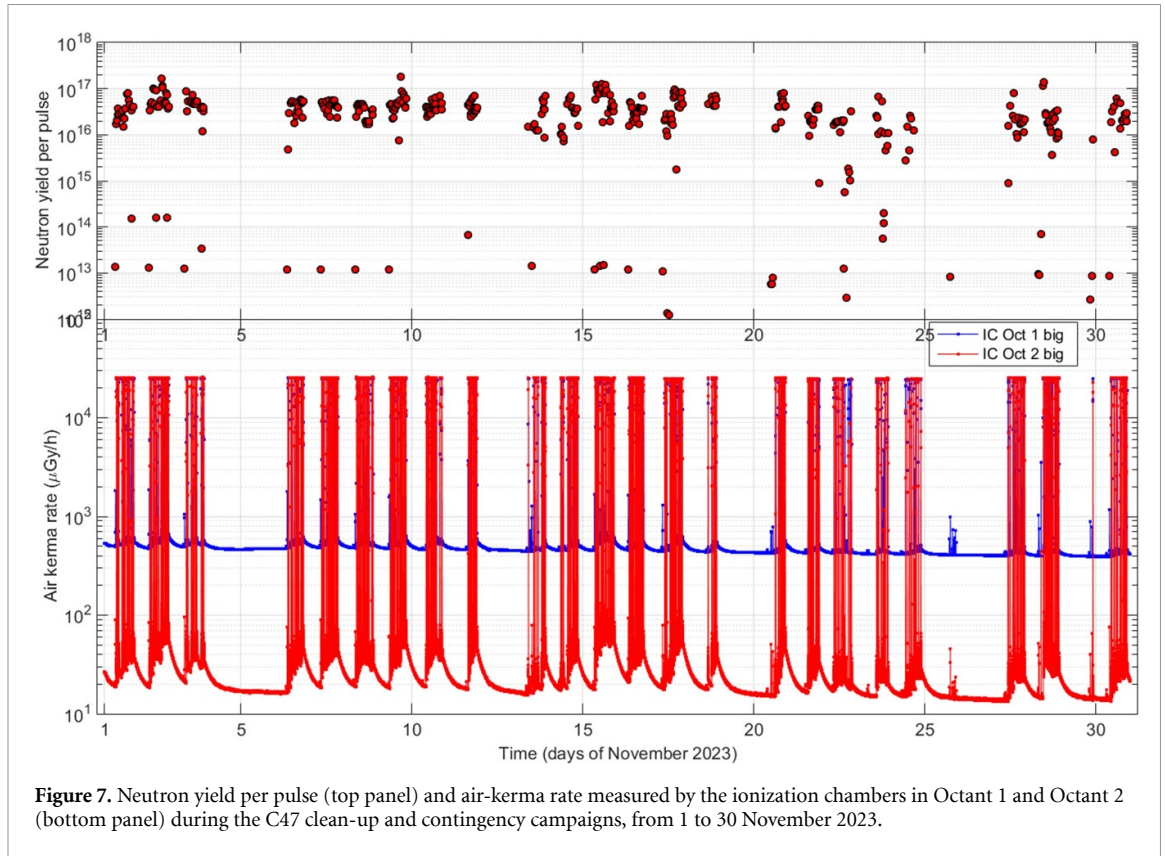
During the clean-up campaign C47, the inter-pulse dose-rate level remained high, at approximately $500 \mu\text{Gy h}^{-1}$ in Octant 1 and approximately $20 \mu\text{Gy h}^{-1}$ in Octant 2, reflecting the residual activation from the intense DTE3 neutron fluence (figure 7). By December 2023 the dose rate had further decreased, to approximately $400 \mu\text{Gy h}^{-1}$ in Octant 1 and approximately $15 \mu\text{Gy h}^{-1}$ in Octant 2, as the short-lived activation products continued to decay while contingency operations were completed.

4.6. JET decommissioning: long-term dose rate trend (2024)

Continuous IC monitoring was maintained throughout the first year of JET decommissioning and beyond, to study the long-term decay. Over the course of one year the SDDR level decreased from approximately $300 \mu\text{Gy h}^{-1}$ to approximately $30 \mu\text{Gy h}^{-1}$ in Octant 1, and from approximately $10 \mu\text{Gy h}^{-1}$ to approximately $3 \mu\text{Gy h}^{-1}$ in Octant 2. In figure 8, the SDDR measured in the first part of January is shown. The boxed interval identifies the measurements selected as reference points, at increasing cooling time, for the JET end-of-life irradiation history (IH#3) used in the benchmark input package.

5. Processed experimental results selected for the benchmark

SDDR tools are based on radiation transport and neutron activation codes. An important step in modeling neutron irradiation is the definition of the irradiation history, calculated from the data collected from the JET neutron monitor KN1. The three irradiation histories (IH#1, IH#2 and IH#3) mentioned



in the previous paragraphs were selected to sample representative points along the DTE3 dose-rate evolution: (i) IH#1, immediately before DTE3, covering cooling times from 3 h to 4 d with respect to the last pulse of 25 August 2023 (cf figure 4); (ii) IH#2, at the end of the DTE3 shutdown, covering cooling times from 3 h to 1 week with respect to the last pulse of 14 October 2023 (cf figure 6); and (iii) IH#3, at the JET end-of-life, covering cooling times from 3 h to 1 year (cf figure 8). Both DT and DD neutron sources are considered in each history, while the contribution of TT reactions, found to be negligible, is disregarded (table 4).

Table 4. Irradiation histories selected for the DTE3 shutdown-dose-rate benchmark analysis.

Irradiation history	From	To	DT yield (n)	DD yield (n)	Total yield (n)
IH#1—before DTE3	30 August 2021	25 August 2023	$8.253\text{E} + 20$	$4.369\text{E} + 19$	$8.690\text{E} + 20$
IH#2—DTE3 shutdown	30 August 2021	14 October 2023	$1.556\text{E} + 21$	$4.369\text{E} + 19$	$1.600\text{E} + 21$
IH#3—JET end-of-life	30 August 2021	18 December 2023	$1.560\text{E} + 21$	$6.718\text{E} + 19$	$1.627\text{E} + 21$

Table 5. Experimental SDDR results with ionization chambers before the start of the DTE3 campaign (irradiation history IH#1), for selected cooling times measured from the last pulse of 25 August 2023.

Cooling time (h)	Cooling time (d)	IC-Oct1-big ($\mu\text{Gy h}^{-1}$)	Uncertainty (%)	IC-Oct2-big ($\mu\text{Gy h}^{-1}$)	Uncertainty (%)
3	0.125	26.0	3.9	4.3	5.42
96	4	18.4	4.0	—	—

Table 6. Experimental SDDR results with ionization chambers at the end of the DTE3 campaign (irradiation history IH#2), for selected cooling times measured from the last pulse of 14 October 2023.

Cooling time (h)	Cooling time (d)	IC-Oct1-big ($\mu\text{Gy h}^{-1}$)	Uncertainty (%)	IC-Oct2-big ($\mu\text{Gy h}^{-1}$)	Uncertainty (%)
3	0.125	3234.7	3.9	655.2	4.2
6	0.25	2211.9	3.9	404.5	4.2
9	0.375	1703.9	3.9	279.9	4.2
12	0.5	1442.0	3.9	215.0	4.2
24	1	1051.6	3.9	119.7	4.2
36	1.5	891.6	3.9	83.0	4.2
48	2	789.6	3.9	61.8	4.2
72	3	671.0	3.9	40.9	4.2
96	4	614.2	3.9	31.3	4.2
120	5	581.5	3.9	26.4	4.2
168	7	554.8	3.9	21.4	4.2

The post-processed SDDR measurements corresponding to the three irradiation histories, expressed in terms of air-kerma rate and its associated relative uncertainty for the two ICs (IC-Oct1-big and IC-Oct2-big), are reported in tables 5–7. Whenever considered too close to the lower limit of the measuring range of dosimeters, measurements are omitted. With respect to the assessment in table 3, repeatability is calculated through statistical analysis of SDDR measurements acquired around the selected cooling time, within a sufficiently short time interval selected on a case-by-case basis. This accounts for the slight discrepancy in uncertainty between the general analysis presented earlier and the results discussed below. These values, extracted from the continuous time series presented earlier at the selected cooling times, constitute the experimental reference against which the predictions of the SDDR tools are compared in terms of Calculated-to-Experimental ratio, C/E.

On the basis of the SDDR measurements described, a complete benchmark input package was prepared and distributed to the NEXP parties for the validation, against the DTE3 experimental campaign, of Rigorous-2-Step (R2S) and Direct-1-Step (D1S) SDDR tools [5]. Several codes are currently under validation through the JET SDDR benchmark, among which are the Advanced D1S [8,9] developed by ENEA and D1S-UNED [23], i.e. the reference code for SDDR analysis of ITER.

5.1. Numerical predictions with advanced D1S

The Advanced D1S dynamic code [8,9], developed by ENEA and progressively extended since its original 2011 formulation, implements the Direct-1-Step approach: neutron transport, radionuclide production and decay-photon transport are coupled within a single MCNP-based simulation, using specially prepared cross-section libraries. Its dynamic variant adds the ability to track changes in machine geometry and source configuration over the course of an irradiation history (a feature that would be very effective for SDDR calculations across the disassembly of JET), to manage multiple component lifetimes and decay-photon source portability, to interface with nuclear data in different formats, and to treat multi-step activation reactions. For the DTE3 analysis, previously validated Octant 1 and Octant 2 MCNP models [4,5] were adapted for coupled neutron/decay-gamma simulation. Neutron and gamma transport used the FENDL-3.1d [24] and mcplib84 [25] nuclear data libraries, respectively, while activation reactions used dedicated D1S libraries derived from FENDL-3.1 c. At each cooling time of interest,

Table 7. Experimental SDDR results with ionization chambers at the JET end-of-life/decommissioning stage (irradiation history IH#3), for selected cooling times measured from the last pulse of 18 December 2023.

Cooling time (h)	Cooling time (d)	IC-Oct1-big ($\mu\text{Gy h}^{-1}$)	Uncertainty (%)	IC-Oct2-big ($\mu\text{Gy h}^{-1}$)	Uncertainty (%)
3	0.125	332.9	3.9	13.8	4.4
6	0.25	328.6	3.9	12.7	4.4
24	1	322.8	3.9	11.5	4.4
168	7	311.0	3.9	10.7	4.5
288	12	297.5	3.9	10.2	4.5
720	30	252.2	3.9	8.9	4.4
1488	62	190.6	3.9	7.1	4.4
2160	90	152.1	3.9	—	—
2904	121	118.8	3.9	—	—
3744	156	91.9	3.9	—	—
4368	182	76.5	3.9	—	—
5088	212	63.7	3.9	—	—
5832	243	52.9	3.9	—	—
8784	366	31.4	3.9	—	—

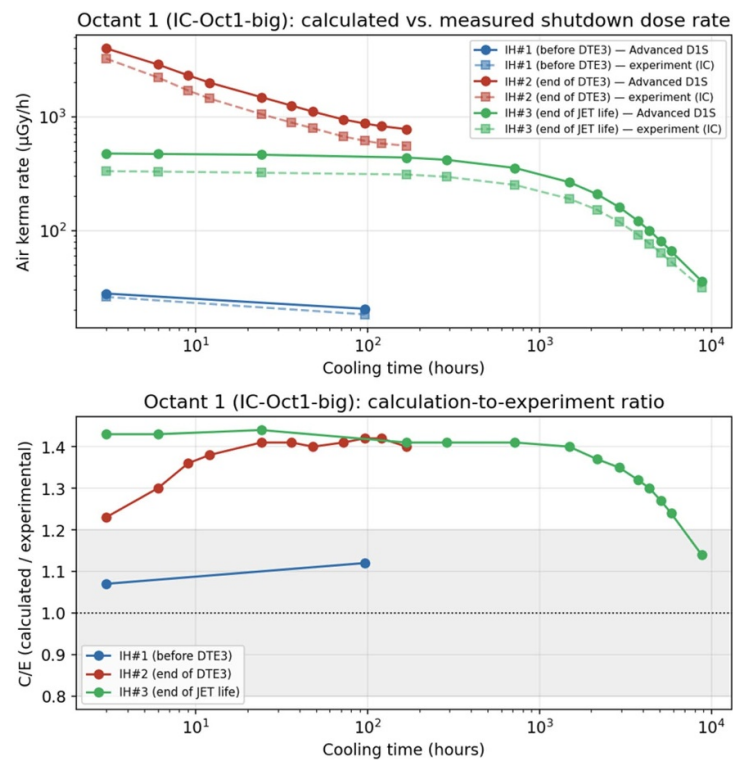
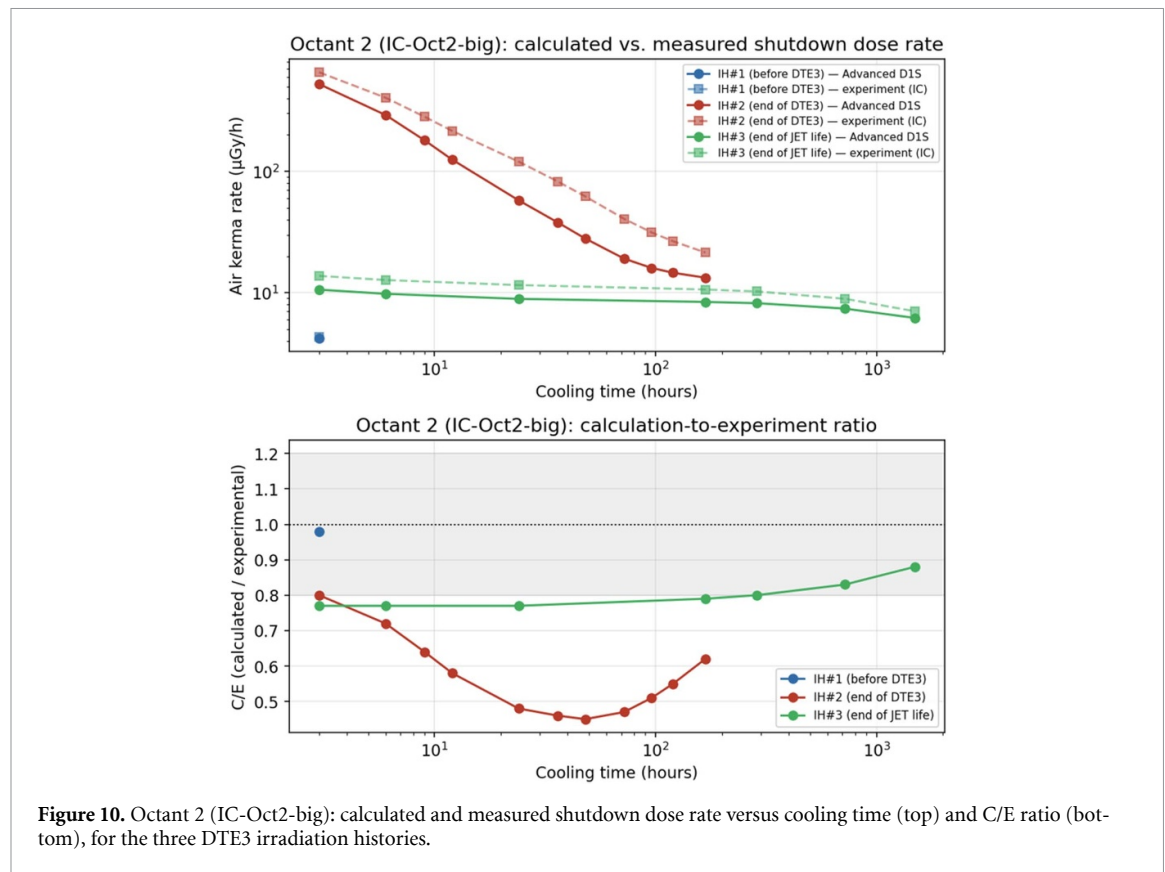


Figure 9. Octant 1 (IC-Oct1-big): calculated (Advanced D1S dynamic) and measured shutdown dose rate versus cooling time (top) and corresponding C/E ratio (bottom), for the three DTE3 irradiation histories.

radionuclide-specific temporal correction factors computed with FISPACT [26] were combined with the Advanced D1S transport results to yield the SDDR within the sensitive volume of each IC. Each irradiation history was simulated with roughly 10^9 source particles on ENEA's CRESCO high-performance computing cluster [27], using 600–800 CPU cores per run.

In Octant 1, the calculated SDDR reproduces the measured temporal trend closely across all three irradiation histories (figure 9). Before DTE3 (IH#1), agreement is very good, with $C/E = 1.07 \pm 0.12$ at 3 h cooling and 1.12 ± 0.13 at 4 d, and the dose dominated (>70%) by Co-60 carried over from DTE2. Immediately after DTE3 (IH#2), the calculation increasingly overestimates the measurement, from $C/E = 1.23 \pm 0.14$ at 3 h to a plateau near 1.40–1.42 beyond about one day—a pattern also seen in the DTE2 benchmark. The dominant isotopes shift over this period from a mixture of Co-60, Mn-56, Co-58 and Ni-57 at 3 h to Co-58 alone accounting for over 90% of the dose after one week. At the end of JET operations (IH#3), the overestimation is largest immediately after shutdown ($C/E = 1.43 \pm 0.16$ at



3 h) and relaxes steadily with cooling time, reaching $C/E = 1.14 \pm 0.12$ after one year, as the Co-58 contribution (initially $>90\%$ at short times) gives way to Co-60 as the dominant isotope after roughly nine months. The recurring overestimation of the Co-58 decay-gamma contribution—produced chiefly through Ni-58(n, p) and Co-59(n, 2n) reactions—points to residual uncertainties in the modeled Inconel and structural-material composition rather than a shortcoming of the transport method itself.

Octant 2 shows a contrasting pattern (figure 10). Before DTE3, agreement is excellent ($C/E = 0.98 \pm 0.12$), with Co-60 ($\sim 80\%$) and Mn-54 ($\sim 12\%$) as the leading contributors. After DTE3, however, the calculation systematically underestimates the measured dose rate, with C/E falling from 0.80 ± 0.09 at 3 h to a minimum of about 0.45 ± 0.07 near 2 d, before partially recovering to 0.62 ± 0.08 at one week. This behavior tracks an evolving isotopic mix—from Mn-56 and Cu-64 at short cooling times, through a Cu-64/Co-58/Co-60 mixture around 2 d, to Co-58, Co-60, Ta-182 and Mn-54 after a week—and is attributed principally to underestimation of the short-lived Cu-64 contribution due to the activation of copper in the poloidal field coil close to the IC. By the end of JET operations, the underestimation eases with cooling time, from $C/E = 0.77 \pm 0.10$ at 3 h to $C/E = 0.88 \pm 0.11$ after 2 months, as Co-58 and Co-60 come to dominate in roughly equal measure. The Octant 2 discrepancies are attributed mainly to geometric and material modeling inaccuracies, particularly an apparent overestimation of the shielding provided by the ITER-Like Antenna structure.

6. Conclusions

This work has retraced the evolution of the JET SDDR dosimetry system, from its original 2015 installation through the DD, TT and DT campaigns to the ongoing final shutdown, and has presented the SDDR dataset acquired during DTE3 and the first year of JET decommissioning. The dose-rate range spanned by the JET measurements presented, from a few $\mu\text{Gy h}^{-1}$ to some tens of mGy h^{-1} , is of direct relevance for ITER, where the design constraints in terms of effective dose for hands-on maintenance operations specify limits of $100 \mu\text{Sv h}^{-1}$ at 12 d after shutdown in the port interspace, and $10 \mu\text{Sv h}^{-1}$ at 1 d after shutdown in the port cell. Although the effective dose per unit air kerma free-in-air depends on energy and irradiation geometry [28], considering the reference antero-posterior geometry and photon energy range 50 keV—some MeV, a conversion factor close to unity can reasonably be adopted to confirm that the measured gamma field is consistent with the effective dose limits stated above.

Building on a rigorous, protocol-based uncertainty budget (1-sigma combined uncertainty of 3.0%–4.2%), three irradiation histories spanning representative stages of the DTE3 (immediately before the campaign, at its end, and at JET end-of-life) were derived and assembled into a benchmark input package that has been distributed to the NEXP collaboration for the validation of Rigorous-2-Step (R2S) and Direct-1-Step (D1S) SDDR tools.

Comparison with Advanced D1S dynamic tool showed good agreement in Octant 1 before DTE3 (C/E close to unity), followed by a recurring overestimation after the campaign that is largest shortly after shutdown and relaxes with cooling time, traced to the Co-58 decay-gamma contribution and pointing to residual uncertainties in the modeled Inconel and structural-material composition. In Octant 2 the opposite trend was found, with a systematic underestimation attributed mainly to an underestimated short-lived Cu-64 contribution from activated copper in the poloidal field coil and to an apparent overestimation of the shielding provided by the ITER-Like Antenna structure. These results confirm the overall validity of the Direct-1-Step methodology that underpins the ITER SDDR safety case, while identifying specific nuclear-data and geometric-modeling refinements needed to further reduce prediction uncertainty.

The JET SDDR program continues beyond the present analysis: the ICs remain in operation throughout the ongoing decommissioning, extending the measured cooling-time range well past one year and providing measurement conditions that are unlikely to be reproduced on any other device. Future work will exploit this unique, continuing dataset to extend the benchmark with additional irradiation histories at longer cooling times, to complete the validation of SDDR tool and to use the observed C/E discrepancies to guide targeted improvements to nuclear data libraries and to the Octant 1 and Octant 2 geometric and material models. This continued effort is expected to further consolidate the experimental basis for the SDDR methodology relied upon for the radiological safety case of ITER.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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