# NEUTRONICS FOR ITER NUCLEAR PHASE: INSIGHTS AND LESSONS LEARNT FROM JET DT OPERATION

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Entering the ITER nuclear phase presents several challenges that must be anticipated and addressed to ensure the project meets its mission objectives. EUROfusion has established an R&D program within the Work-Package Preparation of ITER Operations (WP PrIO) [1] to enhance neutronics, nuclear safety, and validate codes to reduce operational risks. The ITER rebaselining [2], with its accelerated timeline, first-wall material change from beryllium to tungsten, and stepwise licensing, introduces new scientific challenges.

An outstanding and unique amount of nuclear fusion relevant data and experience have been collected from the latest Deuterium-Tritium (DT) campaigns at JET tokamak (DTE2 and DTE3 campaigns), producing $1.57 \times 10^{21}$ DT neutrons [3-5]. Dedicated measurements and analyses were carried-out in the frame of PrIO sub-project “Neutronics, Nuclear Waste, and Safety” to characterise the activation of real ITER materials [6] and the degradation of functional materials, to verify the 14 MeV neutron diagnostics calibration, to test detectors for Tritium Blanket Module (TBM) and to assess the Tritium Breeding Ratio (TBR) predictions in Helium Cooled Pebble Bed (HCPB) TBM mock-up [7]. Benchmark experiments on neutron streaming and shutdown dose rate were performed to validate the computational tools and nuclear data used for ITER nuclear analysis [5, 8]. Unique experiments explored complex phenomena like water activation in JET cooling loops [5] and Single Events Effects (SEE) [9] on electronics during DT plasma operations. For this exploitation, several active and passive detection systems, test assemblies, and samples were located at approximately 30 locations inside the JET vessel, in the torus hall, and in the basement during the DT campaigns.

Main achievements, recent results and lessons learnt for ITER from technological exploitation of JET DT operations are reviewed in this contribution.

**Achievement of 10% accuracy in neutron diagnostics calibration.** In 2017, an absolute calibration of JET main neutron diagnostics, fission chambers (for time-resolved neutron yield rate, KN1) and activation foils system (for integral neutron yield, KN2), was successfully performed using a 14 MeV neutron generator deployed inside the vacuum vessel with power supply, detectors and electronics, via the remote handling system. The calibration was successfully validated during plasma operations in DTE2 and DTE3, achieving the ±10% target accuracy required for neutron yield and yield rate measurements in ITER DT operations. This was accomplished through rigorous methodology, advanced modeling, and cross-calibration, providing valuable insights for future neutron diagnostics calibration in ITER. Demonstrating the accuracy and reliability of fusion power measurements are essential for obtaining approval for tritium operations on ITER and fusion power plants.

**Neutron transport and materials activation: characterisation and experimental validation of nuclear codes.** Experience from JET nuclear operations led to significant development and improvement of neutron and gamma measurement techniques, as well as of neutronics codes used for design and safety analyses. Significant efforts have been made in the experimental validation of the codes used for ITER and DEMO nuclear analysis, including MCNP5/6 with ADVANTG, TRIPOLI-4©, and OpenMC for radiation transport, FISPACT-II for activation, and several MCNP-based Direct 1-step (D1S) and Rigorous 2-step (R2S) approaches for shutdown dose rate calculations. These validations were achieved by comparison between calculations and measurements, revealing in general conservative predictions for maintenance-relevant dose rates and activities. Some discrepancies were also identified mainly due to uncertainties in geometry, material chemical compositions and some code methodology artefacts [5, 6]. Fig.1 shows the comparison between calculations performed with MCNP6 and FISPACT II and measured activity in ITER materials irradiated during DTE2 in Long Term Irradiation Station (LTIS) [6]. In general, good agreement was found across the majority of samples. Some cases with significant C/E discrepancy of the radio-nuclides relevant for maintenance were observed in some materials, for example CuCrZr and W samples. Fig. 2 shows the temporal evolution of the shutdown dose rate close to equatorial port of Octant 1 during the shutdown after DTE2. The results of the calculations with various MCNP-based D1S and R2S tools and measurements are shown. The temporal and dose rate level range are relevant for the shutdown dose rate assessment in ITER and support the validation of the nuclear codes required for safety demonstration. Key factors influencing the accuracy of the simulations have been identified, including the detailed geometric description in neutronics models following machine configuration changes, the correct

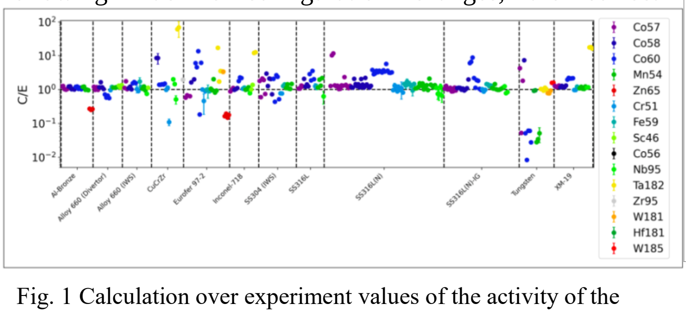


Fig. 1 Calculation over experiment values of the activity of the various isotopes per ITER material irradiated during DTE2 [6].

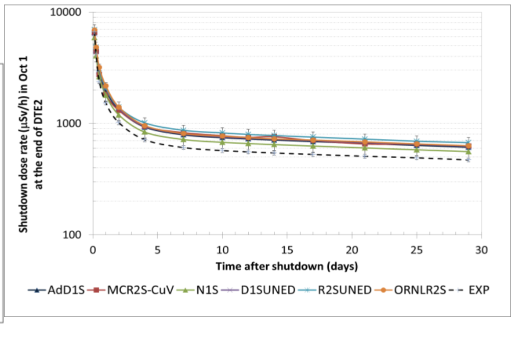


Fig. 2. SDR calculated with various D1S and R2S codes and experimental data in JET Octant 1 during DTE2 shutdown versus cooling time.

specifications of chemical impurities in the materials, the reliability of neutron source representation, the representativeness of irradiation scenario and the quality of the nuclear data. All these elements are essential for reliable predictions and contribute to the reduction of uncertainties.

**Study of degradation of optical transmission in silica optical fiber following DT irradiation.** Optical transmission of silica optical fibers degrades under DT irradiation, showing a clear decrease across 200–1200 nm with increasing neutron fluence ($\sim 5 \times 10^{15}$ cm²) due to radiation-induced defects. The study improves the understanding on neutron-induced defects with direct applications to ITER, where silica and optical fibers play a key role in diagnostic systems.

**TBM detectors tests and validation of TBR predictions.** The MCNP neutron transport simulations showed an underestimation of the TBR measured in HCPB TBM mock-up in DTE2, with a calculation-over-experiment ratio of 0.77, indicating that design calculations provide conservative results for the self-sufficiency of fusion reactor employing a HCPB type breeder blanket. The performances of the TBM detectors provided valuable insights for improvement. Experimental challenges in on-line tritium measurements using diamond detectors in high-performance and harsh environments led to important lessons for future detector design and operation. Furthermore, the study emphasized the importance of further research on Neutron Activation Systems (NAS) for TBM to achieve accurate neutron spectra reconstruction.

**Validation of models and methods for predicting neutron-induced SEE on electronics in tokamak.** Initial studies in 2021 on neutron-induced SEEs in the WEST tokamak provided preliminary validation of models and methods for predicting bit flip rates in SRAMs within a tokamak deuterium plasma neutron environment. The unique SEE experiment performed at JET during the DTE3 campaign confirmed these models and methods in DT, emphasizing the high bit flip rates and reliability challenges expected in ITER and future tokamaks [9]. A reduction in bit flip rate was observed with a local $B_4C$ shield, with further improvements required through an optimized shield design.

**Water activation and understanding complex neutron-induced phenomena.** The water activation experiment performed on JET during DTE3 provides a first-time insight into activated water in tokamak cooling loops, revealing clear effects of plasma scenarios on delayed gamma spectra measurements and water activation peaks from $^{16}N$ decay (Fig. 3). A strong correlation has been observed with plasma operations and circuit parameters [5]. A unique experimental dataset has been developed for validating multi-physics simulation tools used for the assessment of the nuclear loads in sensitive tokamak and plant components for ITER and DEMO. Furthermore, significant knowledge has been acquired for the development of neutron diagnostics based on water activation.

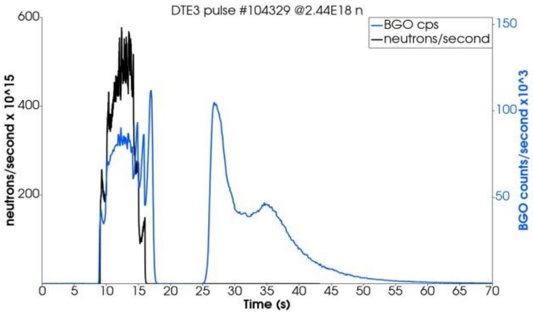


Fig. 3. #104329- KN1 neutron yield rate (n/s) and gamma counts in BGO spectrometer (cps) of the water activation system versus time (s).

The unique results presented in this synopsis provide significant insights for ITER nuclear operations and advance nuclear fusion technology and safety for future reactors.

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## REFERENCES

[1] LITAUDON, X et al., IAEA-FEC 2023, Nuc. Fus. 64 (11) (2024) 112006
[2] BARABASCHI P., SOFT-2024
[3] KAPPATOU, A. et al., EPS-2024 submitted to PPCF
[4] MAGGI, C. et al., IAEA-FEC 2023, Nuc. Fus. 64 (11) (2024) 112012
[5] VILLARI, R. et al., SOFT-2024, under review in Fus. Eng. Des. (2024)
[6] PACKER, L.W. et al., IAEA-FEC 2023, Nucl. Fus. 64 (10) (2024) 106059
[7] FONNESU N., et al. Eur. Phys. J. Plus 139, 893 (2024)
[8] LENGAR, I., et al. Fus. Eng. and Des.. 202 (2024) 114351
[9] DENTAN, M. et al., IEEE Trans. Nucl. Sci., DOI: 10.1109/TNS.2025.3540345