CONFERENCE PRE-PRINT

OPENMC BASED SIMULATIONS FOR SHUTDOWN DOSE RATE ASSESSMENT IN THE DEMO FUSION REACTOR

R.S. AFANASENKO
Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany
Email: roman.afanasenko@kit.edu

D. LEICHTLE, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
J. PARK, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
J. ELBEZ-UZAN, EUROfusion, Garching, Germany
P. PERESLAVTSEV, EUROfusion, Garching, Germany

Abstract

The accurate prediction of Shutdown Dose Rates (SDDR) is a critical aspect of fusion reactor design, directly linked to radiation safety during maintenance and decommissioning. In this study, we present a comprehensive analysis of SDDR for the DEMO tokamak, a next-generation fusion device, using two complementary Monte Carlo transport codes: OpenMC, an open-source platform, and MCNP, the reference tool for DEMO neutronics. The methodology coupled high-fidelity neutron transport simulations with activation and decay gamma transport calculations, enabling the assessment of both in-vessel and ex-vessel radiation fields. Advanced modelling approaches are applied to capture DEMO's complex geometry, heterogeneous material compositions, and operational scenarios. Comparative results demonstrate the influence of spatial discretisation, material activation, and decay source modelling on predicted dose rates, highlighting both consistencies and discrepancies between the two codes. The outcomes provide valuable insights into code verification, shielding optimisation, and the development of maintenance strategies, supporting the safe and reliable deployment of future fusion power plants.

1. INTRODUCTION

The accurate prediction of Shutdown Dose Rates (SDDRs) [1] is a critical requirement in the safety assessment of future fusion power plants, particularly for ITER [2], DEMO [3], and VNS [4], which is foreseen as the first device to demonstrate the feasibility of long-term deduction of DT plasma and first electricity production from magnetic confinement fusion. Reliable SDDR assessments are necessary to verify compliance with occupational radiation protection standards and to determine safe maintenance procedures, component handling strategies, and decommissioning pathways. Given the intense 14.1 MeV neutron fluxes and the subsequent generation of long-lived activation products such as ^{60}Co ($t_{1/2} \approx 5.27$ years), ^{54}Mn ($t_{1/2} \approx 312$ days), ^{59}Ni ($t_{1/2} \approx 76{,}000$ years), ^{183}Ta ($t_{1/2} \approx 5$ days, but strong γ emitter initially) and ^{93}Mo ($t_{1/2} \approx 4{,}000$ years), within the reactor materials, an accurate evaluation of radiation fields is indispensable for both engineering design optimization and licensing activities.

In this work, perform a comparison of SDDR predictions for new DEMO LAR (Low Aspect Ratio) model using two independent Monte Carlo particle transport codes: OpenMC [5], a modern, open-source tool that has recently been extended for coupled neutron–photon transport and activation analyses, and MCNP [6], which remains the reference standard in DEMO neutronics and has been extensively validated for fusion applications. The comparison aims not only to quantify differences in the calculated dose fields but also to assess the robustness, scalability, and reproducibility of advanced open-source tools against well-established industrial benchmarks. Fig. 1 shows a general view of the simplified CAD model of the DEMO LAR tokamak, which was used for neutronic calculations. The model was constructed to balance computational efficiency with physical fidelity, retaining the essential geometric and material details necessary for reliable SDDR assessments. Major tokamak components are explicitly represented, including the plasma chamber, first wall, breeding blanket modules, divertor, vacuum vessel, and selected ex-vessel systems such as shielding structures and maintenance ports.

The blanket system was modelled according to the ceramic breeder concept with Li_8PbO_6 material, surrounded by steel structures and cooling channels. The divertor design incorporates tungsten plasma-facing units with underlying steel supports, enabling the capture of high heat and neutron loads. In addition, penetrations for diagnostic systems and access ports were included in a simplified form to account for streaming effects, which play an important role in dose rate evaluations.

By reducing minor geometric details while preserving the global layout and material compositions, this CAD-based neutronic model provides a robust compromise between accuracy and computational performance.

Its modular structure allows for straightforward adaptation to different irradiation scenarios and blanket design options, making it a versatile tool for parametric studies of DEMO's radiation environment.

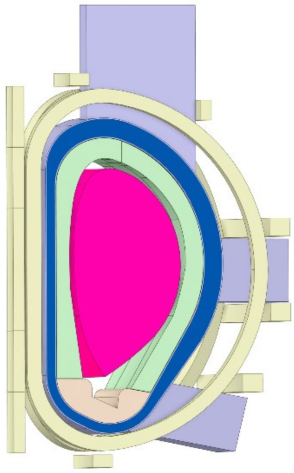


FIG. 1. CAD geometry of the base neutronic 22,5°- degree DEMO LAR 2025 model.

The adopted methodology integrates multi-step radiation transport and inventory simulations, beginning with high-fidelity neutron transport calculations in a detailed DEMO geometry, followed by activation and decay inventory analyses for all relevant materials, and concluding with time-dependent decay γ-ray transport simulations. This workflow allows the determination of the spatial distribution and temporal evolution of shutdown dose rates throughout both in-vessel structures (blanket modules, divertor, first wall) and ex-vessel components (shielding, port structures, maintenance equipment).

By employing advanced modelling techniques such as mesh-based source reconstruction, consistent nuclear data libraries for both neutron and photon transport, and hybrid variance-reduction schemes, the study ensures that the simulations capture the full complexity of the DEMO configuration. The results provide valuable insights into the expected radiation environments during scheduled maintenance and unplanned interventions, highlighting critical hot spots and demonstrating the sensitivity of SDDR predictions to modelling choices. Ultimately, this work contributes to the ongoing international effort to establish reliable computational frameworks for radiation protection assessments in DEMO and subsequent commercial fusion power plants.

2. METHODOLOGICAL APPROACH

The study presents a systematic comparison of the SDDR calculated by OpenMC and a coupled transport-activation code based on MCNP, two widely used Monte Carlo codes for neutron transport and shielding analysis. Both frameworks adopt the Rigorous-2-Step (R2S) methodology [7], which combines high-fidelity neutron transport with activation calculations and secondary gamma-ray transport. The primary objective is to assess the consistency and accuracy of SDDR predictions between the two codes, with emphasis on the influence of spatial discretization strategies, material treatment, and decay source modelling approaches.

2.1. Neutronic model

The methodological framework of this work involves the development of a consistent computational model of the DEMO LAR tokamak environment, including detailed three-dimensional representations of major components such as the blanket modules, divertor, vacuum vessel, and ex-vessel structures. The model has been designed with high geometric fidelity to capture the complexity of the DEMO nuclear environment, enabling accurate simulation of neutron transport, activation, and subsequent SDDRs.

A key feature of the DEMO neutronic model employed in this study is the implementation of a ceramic breeder concept based on Li_8PbO_6 - Water cooled Lead Ceramic Breeder Blanket (WLCB) [8] presented on Fig.2. This breeder material was modeled with a density of 2.74 g/cm³ and an enrichment of ^{6}Li to 90%, thereby maximizing tritium breeding performance under DEMO operational conditions. The use of a ceramic lithium-lead oxide offers specific advantages in terms of chemical stability and tritium recovery, while also presenting unique challenges for neutronics and activation analysis due to its mixed heavy-element composition. The neutronic description incorporated detailed zoning of the breeder, multiplier, and structural regions, as well as the inclusion of cooling channels and support materials, which are critical for accurate prediction of neutron flux spectra and activation inventories.

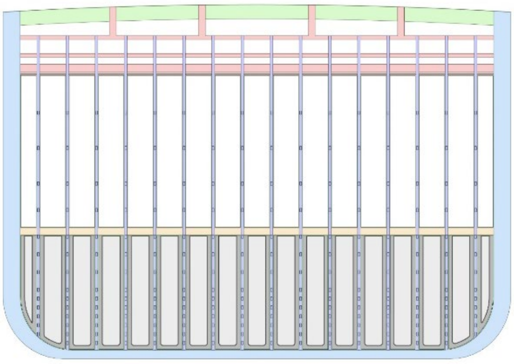
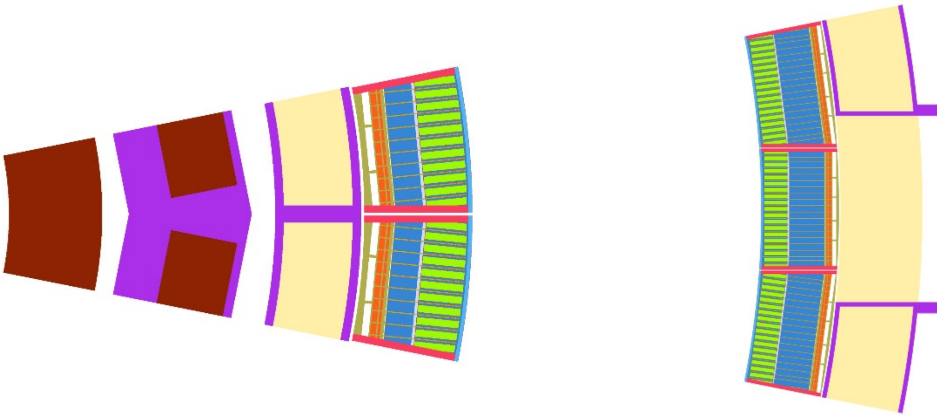


FIG. 2. Horizontal slice of the WLCB blanket implemented in the DEMO LAR 2025 model.

The ceramic breeder configuration was embedded within the blanket modules, which were modeled in a modular arrangement surrounding the plasma. EUROFER steel was adopted as the structural material, providing consistency with current European DEMO design studies. The coupling of enriched Li_8PbO_6 with the steel structures was carefully implemented to ensure that the neutron moderation and multiplication effects were realistically represented.

The figure below presents a horizontal slice of the 22.5-degree DEMO LAR computational model with the inboard (a) and outboard (b) WLCB blanket concept implemented in OpenMC. This slice highlights the spatial distribution of key reactor components and provides a clear view of the structural complexity that must be addressed in neutronic and activation analyses. The plasma chamber, first wall, breeding blanket modules, vacuum vessel, and surrounding shield structures are distinctly visible, illustrating the hierarchical arrangement of materials and regions that strongly influence neutron transport and secondary radiation fields.



a) *b)*

FIG. 3. Horizontal slice of the inboard (a) and outboard (b) WLCB blanket implemented in the 22.5-degree DEMO LAR 2025 model.

The horizontal section is particularly useful for identifying streaming paths and localized shielding challenges, such as those associated with maintenance ports, coolant channels, or diagnostic penetrations. These features, although simplified in the model, play a crucial role in shaping the SDDR distributions, as even minor openings can significantly affect the propagation of activation products and decay gammas. The inclusion of such details ensures that the OpenMC model captures the most relevant physical processes without excessive geometric complexity.

Moreover, the slice emphasizes the implementation of the ceramic breeder blanket based on Li_8PbO_6 with 90% ^6Li enrichment. The arrangement of breeder zones, steel structures, and coolant regions can be directly appreciated from this view, highlighting the layered structure of the blanket system. This representation provides confidence that the computational geometry adequately reflects the functional roles of DEMO components, enabling consistent benchmarking of OpenMC simulations against reference MCNP calculations.

2.2. R2S and D1S methods of the SDDR estimation

The R2S method decouples the problem into two sequential steps: first, neutron transport simulations provide reaction rates and activation inventories within a discretized mesh or material regions; second, decay photon source terms are reconstructed from these inventories and transported independently to calculate dose rates. This approach allows for detailed treatment of activation chains, temporal decay, and spatially resolved gamma emission. The use of mesh-based coupling between neutron and photon transport provides high fidelity, although at the cost of significant computational resources. In this study, the method was implemented using MCNP in combination with the R2Smesh approach developed at KIT [9], and the results were compared with the implementation of the R2S methodology in the OpenMC code, developed by Paul Romano [10].

In contrast, the D1S method implemented in OpenMC integrates neutron transport, activation, and gamma transport into a single step by using pre-computed photon emission libraries that map neutron fluxes directly to gamma sources. This results in a much more computationally efficient workflow, avoiding the need for explicit inventory calculations. However, the accuracy of D1S strongly depends on the assumptions embedded in the photon source libraries, and its ability to represent spatial and temporal variations is limited compared to R2S. As such, D1S is widely used for scoping studies, shielding assessments, and early-stage design evaluations where computational efficiency is prioritized.

2.3. Methodology

The workflow further incorporates activation libraries derived from modern evaluated nuclear data files (JEFF versions 3.3 [11] and 4.0 [12]), enabling a consistent treatment of neutron-induced reactions and subsequent radionuclide inventories. Following neutron transport simulations, decay photon sources are generated and propagated to determine time-dependent dose rates at both in-vessel and ex-vessel locations.

A key aspect of the comparison is the evaluation of spatial and temporal discretization effects. The computational meshes used for source generation are varied in resolution to study their impact on the fidelity of the activation and gamma transport steps. Similarly, different temporal cooling steps are analysed to investigate the accuracy of dose rate predictions from short cooling times (hours to days) dominated by short-lived isotopes like ^{54}Mn, ^{60}Co, ^{58}Co, ^{181}W, which are strong γ-emitters; to longer timescales (months to years) where long-lived activation products such as ^{60}Co, ^{59}Ni, ^{94}Nb, and ^{41}Ca become increasingly relevant. The inclusion of both short- and long-lived radionuclides ensures a comprehensive assessment of dose rates relevant to maintenance schedules and decommissioning strategies.

Beyond numerical consistency, this study also highlights practical considerations for the application of transport-activation workflows. OpenMC's native integration with Python-based analysis tools allows greater automation and reproducibility of large-scale calculations, whereas MCNP-based workflows often rely on external coupling scripts. The ease of integrating OpenMC into advanced uncertainty quantification or sensitivity studies may prove advantageous in the long term. Nevertheless, careful cross-code validation, as performed here, is essential to ensure the robustness of predictions given the high safety standards required in nuclear fusion projects.

The results contribute to the verification and validation of modern Monte Carlo transport codes, an essential step for licensing and safety assessment of future fusion power plants. Also, they provide valuable guidance for the optimization of computational workflows in large-scale reactor analyses, particularly regarding the balance between mesh resolution, run time, and predictive accuracy. Ultimately, this work demonstrates that OpenMC and MCNP, when applied with consistent modelling strategies, can deliver reliable SDDR predictions for DEMO, supporting ongoing international efforts to establish robust safety frameworks for the next generation of nuclear fusion reactors.

2.4. Irradiation scenario

The irradiation scenario considered in this work represents the first operational phase of the DEMO LAR tokamak and was designed to provide a realistic basis for the preliminary estimation of SDDRs. The scenario consists of a one-month irradiation history, combining both reduced and full-power operating conditions to capture representative neutron loading patterns within the reactor components.

For the majority of this phase, DEMO is assumed to operate at 30% of its nominal fusion power for a duration of 29 days. This reduced-power operation serves to approximate the conditions of early commissioning or initial testing campaigns, during which thermal and mechanical stresses on the plasma-facing components and blanket modules are intentionally minimized. Despite the reduced power, such an operation provides a sufficiently high integrated neutron fluence to activate structural and breeder materials, making it suitable for initial dose rate assessments.

The reduced-power phase is followed by a series of ten high-power plasma pulses, simulating transient full-load operation. Each pulse corresponds to 2.11 hours of irradiation at 100% nominal fusion power (1651 MW), separated by cooling intervals of 1000 seconds. This pulsed sequence was introduced to evaluate the short-term activation and decay behaviour of critical in-vessel and ex-vessel components under cyclic high-flux conditions. The combination of steady reduced power and transient full-power pulses provides a comprehensive irradiation history that reflects both baseline and peak operational challenges.

Overall, this first-phase irradiation scenario was specifically developed for preliminary shutdown dose rate evaluations. It allows for the quantification of early-time activation products and their decay characteristics, thereby offering insight into the accessibility of reactor components during maintenance after short-term operation. The results obtained from this scenario form the foundation for subsequent analyses with longer and more complex operational histories, ultimately supporting the optimization of shielding and remote-handling strategies for DEMO.

3. NEUTRONIC COMPUTATIONAL RESULTS

The computational results clearly demonstrate the dominant influence of neutron-induced activation on the SDDR within fusion devices. During the baseline DT irradiation scenario, characterized by full-power operation (P_{fus}=1651 MW) of the DEMO-LAR tokamak, the calculated SDDR inside the Vacuum Vessel (VV) significantly exceeds permissible occupational limits. The simulations highlight the severe radiation environment of in-vessel components, with dose rates for highly activated regions such as the WLCB blanket modules implemented in the model and divertor assemblies reaching several kSv per hour immediately after shutdown. In particular, the FW, which is subjected to the highest neutron fluxes and energy deposition, is identified as the most critical component. After 12 days of cooling, the SDDR in the FW remains at approximately 100 Sv/h, orders of magnitude above safe exposure limits. This outcome underlines the necessity of careful selection of low-activation structural materials and optimization of cooling intervals to minimize radiation risks.

By contrast, the ex-vessel regions experience substantially lower radiation levels due to geometric attenuation and shielding effects. In these zones, the SDDR was consistently below 0.1 Sv/h, even immediately following shutdown, and decreased rapidly with cooling time. Such results suggest that ex-vessel access could be achievable on shorter timescales compared to in-vessel regions, enabling partial maintenance activities while the central components remain inaccessible. This differential behavior between in-vessel and ex-vessel areas underscores the importance of spatially resolved SDDR analyses, rather than relying on volume-averaged metrics. The analysis also evaluated the impact of reduced operating power on activation and subsequent dose rates. When the fusion power was decreased to 30% of the baseline irradiation scenario, the SDDR in the FW decreased by nearly a factor of two. This non-linear reduction indicates that material activation processes depend strongly on neutron flux intensity and spectrum, suggesting that careful control of plasma operational scenarios can provide additional flexibility in radiation management. Such power modulation strategies may play an important role in extending component lifetimes and reducing the frequency of high-radiation maintenance campaigns.

The computational results also shed light on the temporal decay characteristics of SDDR, which are governed by the half-lives of dominant activation products. Short-lived isotopes drive the rapid decrease observed within the first days and weeks, while long-lived species such as ^{60}Co, ^{59}Ni, and ^{94}Nb sustain elevated dose rates over longer periods. Understanding these decay trends is crucial for scheduling maintenance campaigns, designing interim storage solutions, and planning decommissioning strategies for activated components.

The results indicate a less 10% difference in dose rates at cooling times of 12 days when compared to the reference R2Smesh approach (based on MCNP), highlighting the need for further refinement of the model and resolution of the mesh. Additionally, it is estimated that a smaller mesh voxel size is required to achieve results within approximately 5% of the R2Smesh reference values for mesh resolutions finer than 5 cm. This highlights the trade-off between computational efficiency and accuracy. Early sensitivity analyses reveal that input parameter uncertainties can lead to dose rate deviations of up to 10-15%. These findings emphasize the importance of optimizing mesh resolution, computational resources, and input data precision to ensure reliable long-term dose rate predictions.

OpenMC has been successfully applied for SDDR calculations, demonstrating its effectiveness as a Monte Carlo radiation transport code. A notable advantage of OpenMC is its internal compatibility with the Rigorous Two-Step and D1S methodologies, a widely adopted approach for SDDR analysis. The results indicate excellent agreement between OpenMC and MCNP, a well-established benchmark code, in predicting SDDR values. This agreement highlights OpenMC's reliability and computational efficiency, positioning it as a viable alternative for SDDR calculations in nuclear engineering applications.

The results demonstrate that both OpenMC and MCNP provide broadly consistent predictions of the SDDR, particularly in regions of high neutron flux close to plasma-facing components. However, differences emerge in low-flux regions and shadowed geometries, where the treatment of secondary gamma sources and mesh discretization schemes play a critical role. OpenMC, benefitting from its fully open-source architecture and modern parallelization strategies, shows potential advantages in flexibility and scalability, while MCNP retains its position as a reference code due to its extensive benchmarking history and validated nuclear data integration. These differences, while modest in magnitude, may have important implications for safety margins and the optimization of shielding design in DEMO.

4. CONCLUSIONS

This study provides a robust framework for Shutdown Dose Rate analysis in fusion facilities, leveraging OpenMC's flexibility and scalability to address the unique challenges posed by next-generation tokamaks. The increasing complexity of devices such as DEMO demands modelling tools capable of handling large-scale geometries, heterogeneous material inventories, and intricate operational scenarios. By systematically integrating neutron transport, activation, and decay photon transport within the Rigorous-2-Step methodology, this work demonstrates the feasibility of high-fidelity SDDR predictions using open-source tools, while also benchmarking their results against the reference standard, MCNP.

The results underscore the necessity of customised shielding strategies and maintenance protocols to ensure compliance with the stringent safety objectives established for nuclear facilities. Even modest discrepancies in predicted dose rates, particularly in shadowed or ex-vessel regions, may influence remote handling operations, shielding material selection, and component replacement schedules. The study shows that accurate prediction of spatial distributions of dose rates is just as critical as global average values, since localised radiation "hot spots" can dominate occupational exposure scenarios. These findings highlight the importance of tailoring SDDR assessments to the specific geometric and operational characteristics of each fusion device.

The integration of OpenMC into the design cycle allows for automated, scalable analyses that can be coupled with uncertainty quantification frameworks and optimisation algorithms. This capability facilitates rapid design iterations and supports licensing activities, where regulatory bodies require transparent and reproducible safety assessments. Finally, this study contributes to the global transition toward clean and sustainable energy sources by strengthening the safety case for fusion energy. By providing validated computational methods for predicting radiation fields and residual dose rates, the work enhances confidence in the feasibility of safe maintenance operations in fusion power plants. It also reinforces the role of advanced computational tools in guiding material development, shielding optimisation, and remote handling technology. In doing so, the research establishes OpenMC and related open-source platforms as critical elements in the toolbox of fusion reactor designers, ensuring that safety remains central to the realisation of fusion energy as a practical power source.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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