1. INTRODUCTIONS

For the study and qualification of structural materials used for the design, licensing, and reliable operation of fusion reactors such as DEMO, the International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source (IFMIF-DONES)[1] is being built to utilize a 125 mA and 40 MeV deuteron beam to produce intensive neutron in the flux of 10^{14}-10^{15} n/cm^2/s. Neutron serves as a critical tool for irradiating and testing material samples, while also posing significant radiation safety considerations.

2. KEY CHALLENGES AND ACHIEVEMENTS

The nuclear analysis of the accelerator system (AS) presents significant challenges due to the complex simulation of coupled particles in beam-on and beam-off operations – deuterons, secondary neutrons, prompt and decay photons. Assumptions regarding beam power, beam time and beam losses have significant impacts on radiation distributions, which vary during normal operation and the commissioning phase. Recently, radiation doses have been comprehensively computed in the three phases of accelerator commissioning, as well as normal operations (Figure 1), by considering the radiation sources produced within the accelerator vault, along with back-scattered neutrons and photons from the test cell. ALARA (As Low As Reasonably Achievable) optimizations have been implemented for safety-class machine protection systems such as the fast isolation valve, as well as diagnostics and beam monitors. The activation of water used for cooling the scraper and beam dump, and the activation of argon and air within the AS rooms, has been recently assessed to mitigate excessive radiation and contamination of cooling loops and ventilation systems. Furthermore, the impact of radiation from the accelerator rooms on neighboring cells has been quantified, taking into account the design baseline of ventilation penetrations, waveguides, cable trails, and other penetrations.

The neutronics analysis on the Test Systems (TS) focuses on both the effective utilization of neutrons for material irradiation and the efficient shielding of radiations. For material irradiation, the beam footprint must be fine-tuned to maintain a lower gradient while ensuring sufficient volume for high DPA (displacement per atom) irradiation. In addition, neutron shielding and heat removal require complex deep penetration simulations using Monte Carlo methods, incorporating state-of-the-art variance reduction techniques. Recent studies with the baseline beam footprint have provided detailed irradiation data on actual geometries of EUROFER specimens, obtaining available volume at different temperature ranges, gradient analysis, spectra analysis, damage dose and gas productions. For radiation shielding, comprehensive dose maps have been computed on the full-detailed test cell (TC) model with small and large penetrations (Figure 2), as well as nuclear responses such as nuclear heating, DPA, and gas production, to evaluate structural integrity and re-weldability. The radiation doses on silicon-based materials and insulation materials used in cable connectors have also been computed. Furthermore, neutron streaming to the upper part of the test cell is mitigated, where numerous cables, cooling pipes, and gaps are present. The activation of water in the cooling system has been studied on the actual cooling loop layout, with dominant isotopes such as N-16, N-17, O-15, and activated corrosion products being considered. The activation studies of air within the shielding blocks reveal non-negligible impacts. Finally, radiation streaming to the lithium loop cell below the test cell and the complementary experimental room downstream of the neutron beam, has been thoroughly investigated to ensure effective radiation shielding, as well as characterizing the neutron field for additional experimental activities.

In the lithium system, the main radioactive source terms include Be-7 and tritium, produced by the activation of lithium, and activated corrosion products (ACP) from EUROFER and stainless steel. The challenges lie in the multi-physics simulation of the production and decay of radioisotopes, alongside the transfer and deposition of these impurities, which depend on factors such as mass flow rate, temperature, nitrogen concentration, and the material of different sections of the lithium loop. Recently, studies have been devoted to determine the production rate of these radioisotopes in various sections of the lithium loop in (TC) under deuteron and neutron activation. These studies are coupled with mass transfer analysis, considering the solubilities of elements under varying temperatures, to finalize the distribution of radioisotopes within different sections of the lithium loop during operations, as well as after shutdown when the lithium film remains attached to the inner surfaces of the piping and container. Radiation maps have been produced using state-of-the-art source modeling tools to simulate detailed piping within the lithium loop rooms.

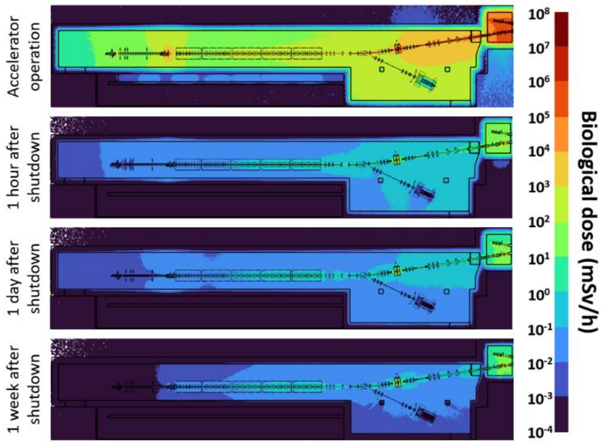

Figure 1 The beam-on total dose rate (mSv/h) contributed by neutron and photon, and the beam-off dose at the cooling time of 1 hour, 1 day and 1 week.

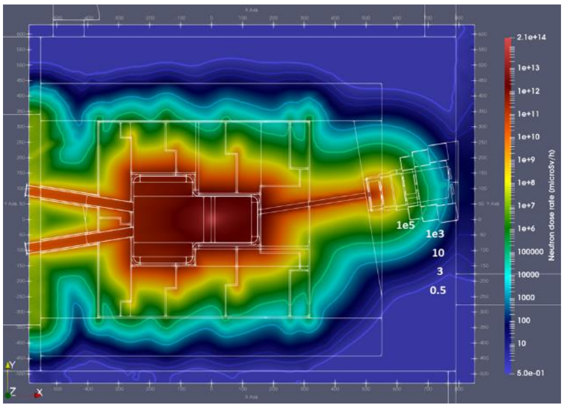

Figure 2 The neutron dose maps (µSv/h) of the TC with the neutron beam shutter closed, horizontal cut at beam level

Efforts are also devoted to assessing radiation safety during maintenance, waste management, and public exposure. The cumulative doses associated with transporting activated components, e.g. the HEBT scraper, beam dump cartridge, target assembly, and test modules, to the irradiating waste treatment and storage rooms are computed using state-of-the-art tools. Radiation sources for other liquid wastes, including wastewater and lithium, are estimated based on design assumptions. The wall thickness required for gamma radiation protection is confirmed based on the radiological classification of these rooms and adjacent areas. Additionally, the sky-shine effect during facility operation and maintenance is thoroughly analyzed in conjunction with direct radiation from downstream rooms, where the radiation protection weakness are identified and improved.

3. SUMMARY

This work aims to provide a comprehensive overview of challenges and recent achievements of neutronics studies and nuclear analyses, starting with the accelerator where neutron and gamma generation from deuteron losses and deposition, progressing to the test system where most d-Li neutrons are produced, and then to the systems and area where the radiation is impacted. These analyses provide key data for the design, safety and licensing of DONES facility and allow it enter the construction and commissioning phases.

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[1] W. Królas et al., The IFMIF-DONES fusion oriented neutron source: evolution of the design, Nuclear Fusion 61 (12), 125002 (2021).