Radiation shielding
of small modular reactor refueling machine

Department:	Department of Power Engineering
Research report no.:	22190 – 007 – 2024
Report type:	Research report
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Pages:	30
Release date:	24.06.2024
CEP Classification:	2.3 Mechanical engineering - Nuclear related engineering (nuclear physics to be 1.3)

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This work has been supported by TACR project TN02000012, working package DP_04_01_03.

Abstract

This research report deals with the radiation shielding analysis of a refueling machine for a TEPLATOR small modular reactor that has the option to use spent nuclear fuel in the reactor core, which is achieved by using heavy water as the coolant and moderator. The refueling machine deals with the transfer of nuclear fuel between the TEPLATOR reactor core in a heavy water environment and the spent fuel storage pool with light water coolant. Radiation shielding of dried fuel assembly inside the refueling machine comprises neutron and photon shielding materials with shielding design based on Monte Carlo calculations.

Keywords

Radiation shielding, small modular reactor, TEPLATOR, spent nuclear fuel

List of symbols and shortcuts

efpd	effective full-power days
FA	Fuel assembly
LEU	Low-enriched uranium
MTU	Metric tonnes of uranium
SMR	Small modular reactor
SNF	Spent nuclear fuel

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1 Introduction

The TEPLATOR reactor is a novel nuclear reactor concept designed for efficient and cost-effective district heating and low-temperature applications. Utilizing spent nuclear fuel (SNF) and low-enriched uranium (LEU), it aims to reduce nuclear waste while providing a sustainable heat source. Operating at lower temperatures than traditional reactors, the TEPLATOR ensures enhanced safety, making it ideal for residential and industrial heating. Its passive safety systems, modular construction, and scalability offer economic and environmental benefits by lowering fuel costs and reducing carbon emissions. The TEPLATOR's robust containment and advanced control mechanisms further contribute to its reliability and minimal environmental impact. By addressing both heating needs and nuclear waste management, the TEPLATOR reactor represents a significant advancement in the application of nuclear technology for non-electric purposes.

This report focuses on the refueling machine, a critical component in the operation of the TEPLATOR reactor. This machine is responsible for the safe and efficient transfer of nuclear fuel between the reactor core, used in a heavy water environment, and the spent fuel storage pool, which uses light water as a coolant. The complexity of this process necessitates thorough radiation shielding to ensure the safety of personnel and the environment.

Radiation shielding of the dried fuel assembly inside the refueling machine is a crucial aspect of its design. The shielding must effectively mitigate neutron and photon radiation to protect against harmful exposure. This is achieved through specialized shielding materials designed and optimized based on Monte Carlo calculations. Monte Carlo methods are employed to simulate radiation interactions with matter, providing detailed and accurate predictions of shielding effectiveness.

The report will delve into the specifics of the shielding design, including the selection and arrangement of materials, the geometric configuration of the shielding, and the results of the Monte Carlo simulations. These simulations are pivotal in determining the optimal shielding design, ensuring it meets safety standards and regulatory requirements.

Overall, this research aims to contribute to developing safe and effective radiation shielding solutions for the TEPLATOR refueling machine, facilitating the use of spent nuclear fuel in a small modular reactor. The report supports the broader goal of advancing nuclear technology for sustainable and efficient energy production by addressing the challenges associated with radiation shielding.

2 Spent nuclear fuel characteristics and radiation sources

The chapter contains the depletion calculation of VVER-440 nuclear fuel in the VVER-440 reactor environment and subsequently in the TEPLATOR reactor environment. The inventory calculation leads to the determination of the characteristics of the spent fuel, which include the decay heat (residual power) and the radiative sources of neutrons and photons.

2.1 Calculation model

The TRITON/NEWT sequence from the SCALE package [1] is a computational tool for reactor physics and fuel depletion analysis, integrating advanced transport and depletion solvers. NEWT, a two-dimensional discrete ordinates transport code within TRITON, enables detailed spatial modeling of reactor cores and complex geometries. This integration allows for accurate simulation of neutron flux distributions and subsequent isotopic changes in nuclear fuel over time. The TRITON/NEWT sequence was utilized for depletion calculations of VVER-440 reactor fuel, see Fig. 2.1 for model in VVER-440 environment and Fig. 2.2 for model in TEPLATOR environment.

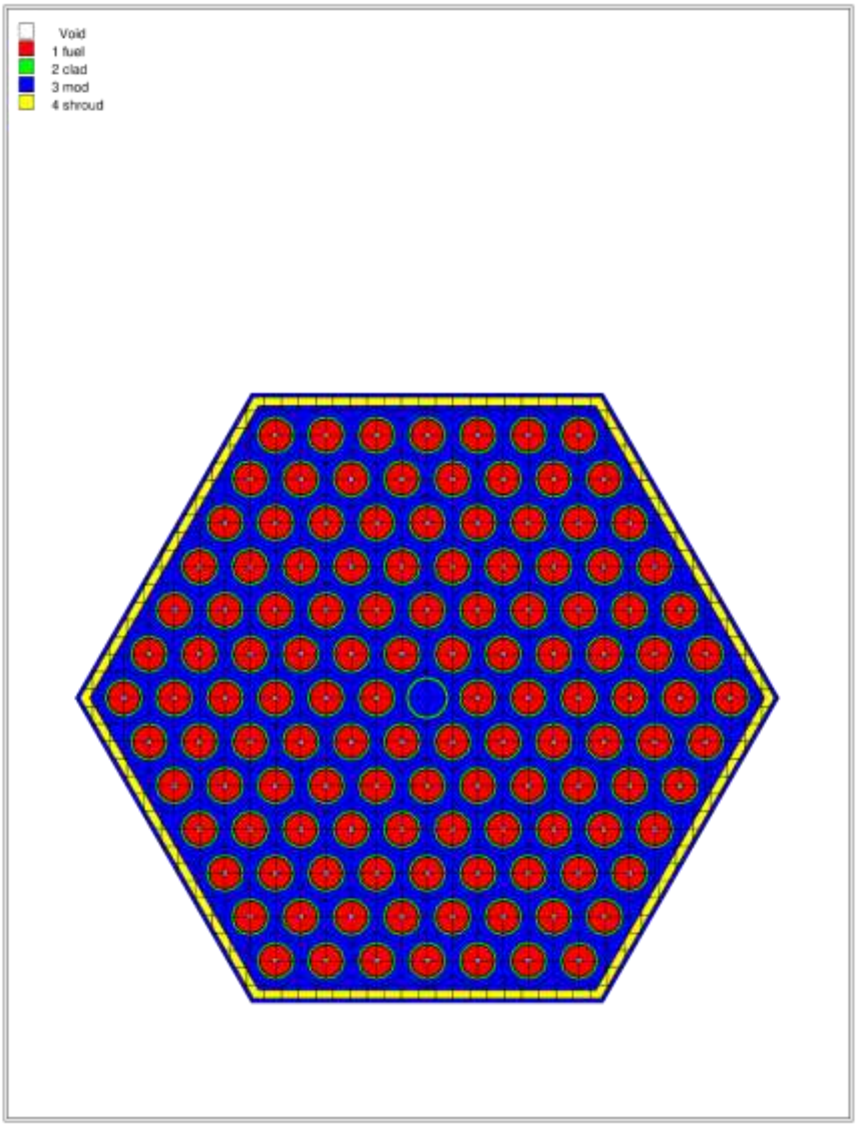

Fig. 2.1 VVER-440 fuel assembly depletion model in VVER-440 reactor

The TEPLATOR small modular reactor (SMR) offers two primary fuel options: low-enriched uranium (LEU) and spent nuclear fuel (SNF). Each option presents unique advantages and challenges, contributing to the reactor's versatility and sustainability.

LEU is uranium enriched to contain a higher concentration of the fissile isotope U-235, typically between 3% and 5%, compared to natural uranium, which has about 0.7 wt% U-235. However, in the case of TEPLATOR, only equivalent SNF fuel with enrichments between 0.9 wt% and 1.1 wt% U-235 are required. Fuel burnup of 2,300 MWd/MTU corresponds to 300 effective full-power days [2]. The TEPLATOR reactor power is 50 MW, which at 55 FA gives a specific power of only 7.5632 MW/MTU.

The TEPLATOR reactor extends the life and utility of nuclear fuel initially used in VVER reactors. Initially, the fuel undergoes irradiation in VVER reactors, achieving significant burnup levels. The most common fuel enriched to 3.60 wt% U-235 reached an average burnup of 35,000 MWd/MTU with a 4,000 MWd/MTU standard deviation. The second widely used design involved profiled fuel with a higher enrichment of 3.82 wt% U-235, achieving a burnup of 44,000 MWd/MTU ± 2,000 MWd/MTU. Despite being classified as spent after this extensive use, these fuel assemblies still contain valuable fissile material. In the TEPLATOR reactor, which uses heavy water as both coolant and moderator, this SNF can be further utilized. The heavy water environment enhances neutron economy, enabling the TEPLATOR to effectively extract additional energy from the residual fissile material in the SNF. Specifically, the TEPLATOR reactor can achieve an additional burnup of approximately 2,300 MWd/MTU from the SNF.

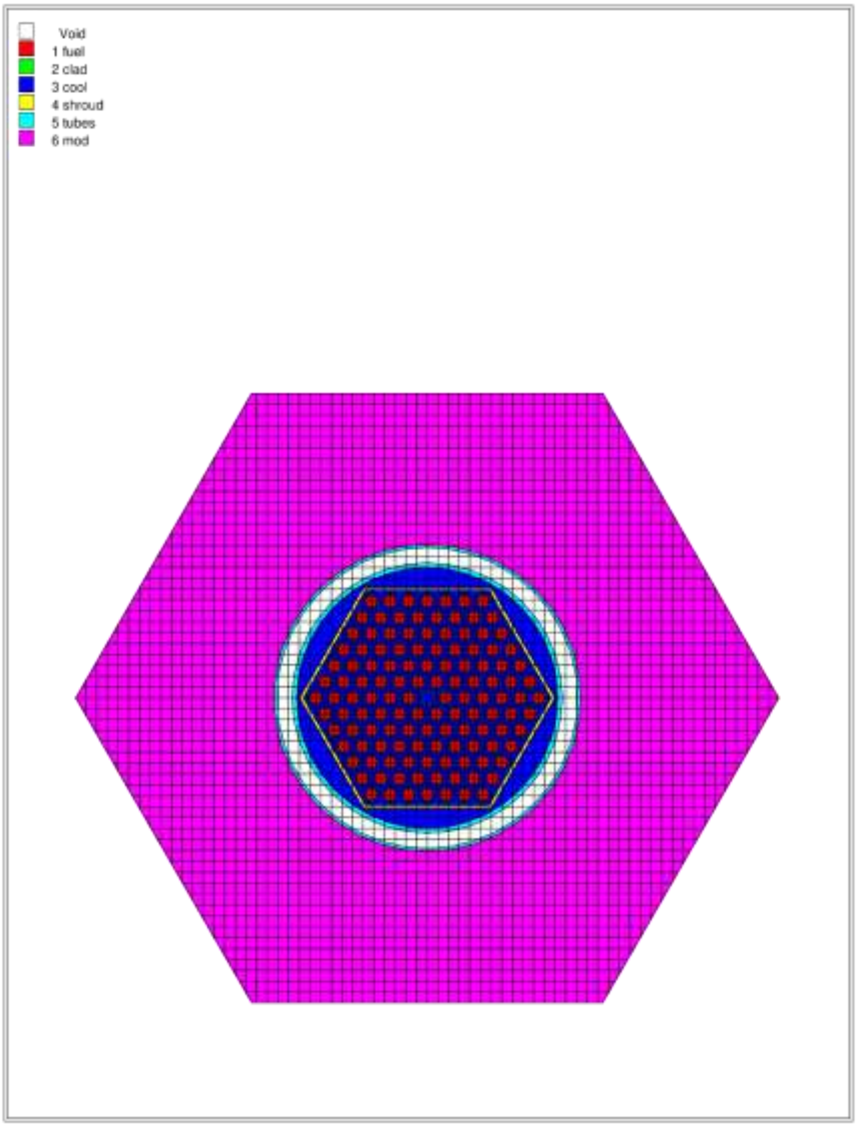

Fig. 2.2 VVER-440 fuel assembly depletion model in TEPLATOR reactor

2.2 Decay heat results

A comparison of the decay heat of the possible fuel assemblies in TEPLATOR is part of Fig. 2.3. This comparison highlights the differences in decay heat between Low-Enriched Uranium (LEU) fuel and Spent Nuclear Fuel (SNF) under various conditions. During the initial days after the fuel is discharged from the reactor, the decay heat is predominantly determined by short-lived fission products. The concentration of these short-lived fission products is influenced more by the reactor power than the fuel burnup. Consequently, at the beginning of the cooling period, the decay heat levels of all fuel types are relatively comparable, regardless of their burnup history.

As the cooling time progresses, differences in the decay heat between LEU and SNF become more pronounced. SNF, which has undergone higher burnup, retains a higher concentration of longer-lived fission products and actinides. This results in higher decay heat for SNF than LEU, particularly noticeable as the short-lived isotopes decay and the influence of the longer-lived isotopes becomes more significant. The highest enrichment and burnup fuel demonstrates the highest decay heat over extended cooling periods.

These differences are critical when considering the handling and management of the fuel assemblies post-reactor operation. Fig. 2.4 includes the envelope values of decay heat, which are particularly relevant from the perspective of the loader equipment used to handle the fuel. The loader must be designed to manage the thermal and radiological characteristics of the fuel, ensuring safe and efficient transfer and storage. Higher decay heat in SNF necessitates enhanced cooling and shielding measures compared to LEU.

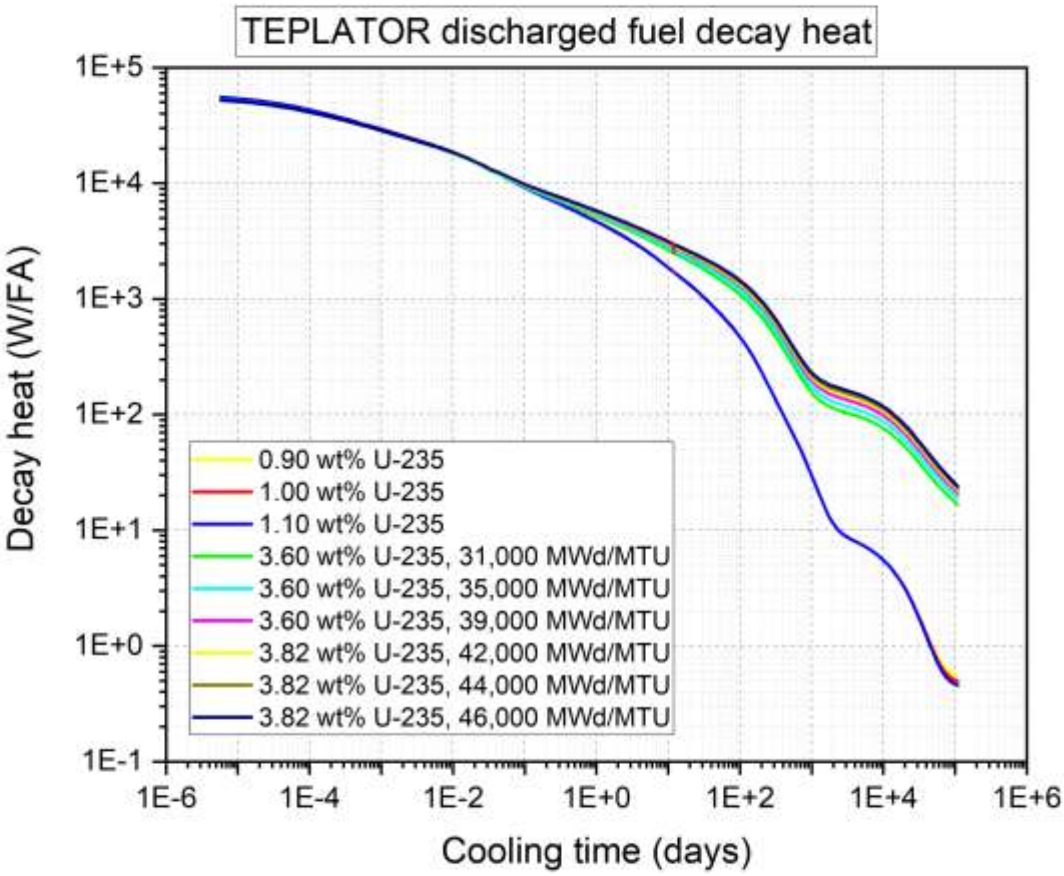

Fig. 2.3 TEPLATOR fuel decay heat comparison

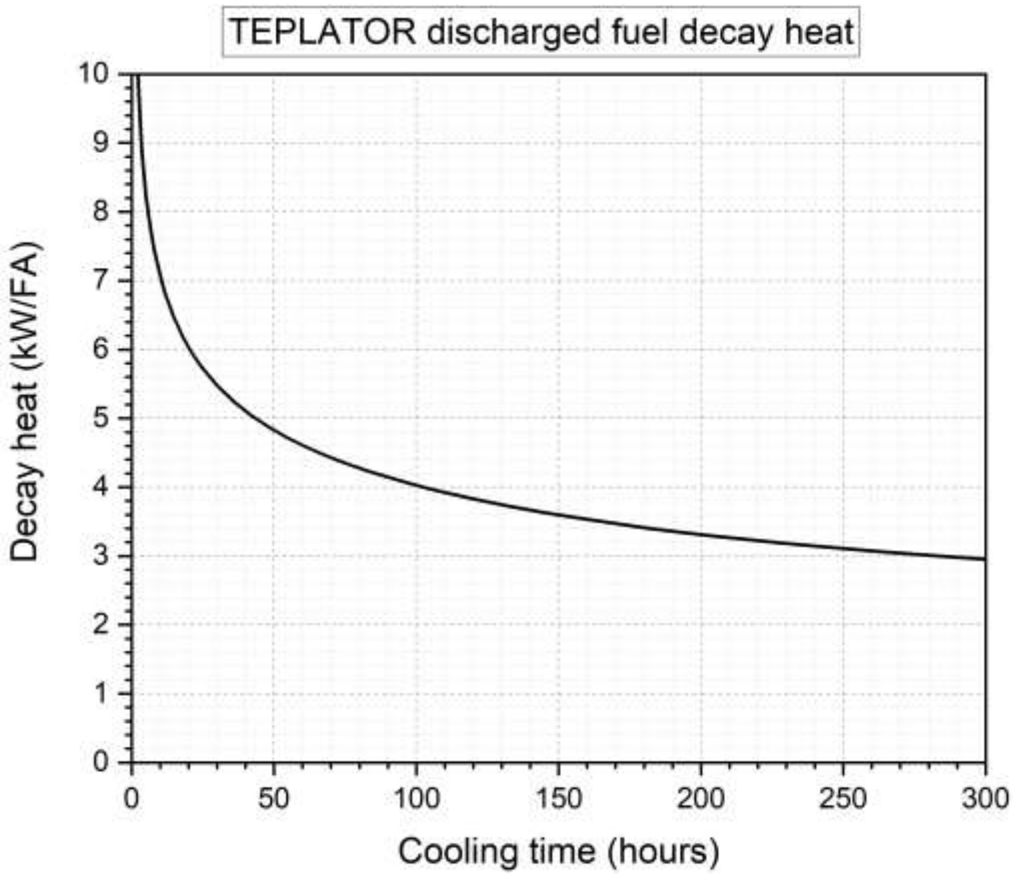

Fig. 2.4 TEPLATOR fuel decay heat during fuel transfer

2.3 Radiation sources results

A comparison of the photon source strength of the possible fuel assemblies in TEPLATOR is shown in Fig. 2.5. This comparison highlights the differences between fuels under various conditions. During the initial days after discharge, photon source strength is predominantly determined by short-lived fission products, influenced more by reactor power than fuel burnup. Thus, initially, photon source strength levels of all fuel types are relatively comparable, similar to decay heat. Having undergone higher burnup, SNF retains a higher concentration of longer-lived fission products and actinides, resulting in higher photon source strength than LEU over extended periods. Fuel with the highest enrichment and burnup demonstrates the highest photon source strength, mirroring the behavior of decay heat.

Fig. 2.6 includes envelope values of photon source strength, particularly relevant for the refueling machine to handle the fuel. The refueling machine must manage the radiological characteristics of the fuel, ensuring safe and efficient transfer and storage. Higher photon source strength in SNF necessitates enhanced shielding measures compared to LEU.

A comparison of the fuels from the neutron source perspective is made in Figure Fig. 2.7 and Fig. 2.8. In contrast to the photon source, the neutron source is higher actinides, mainly Cm-242 and Cm-244, with long half-lives, whose concentration depends mainly on the fuel burnup. The neutron source is significantly higher for fuel with 3.82 wt% U-235 enrichment. The concentration of actinides is practically unchanged during the relevant cooling times after the effect of delayed neutrons wears off.

The displayed neutron source is independent, meaning the effect of subcritical multiplication is not included. In the case of a single fuel assembly in the revolver of the refueling machine, the multiplication coefficient is around 0.2 for heavy water and 0.4 for light water. The independent neutron source is multiplied by a 1/(1-k) factor. In a dry state, the multiplication coefficient is negligible. The higher multiplication coefficient for a single fuel assembly in light water compared to heavy water is due to the small spacing of the fuel rods in VVER fuel.

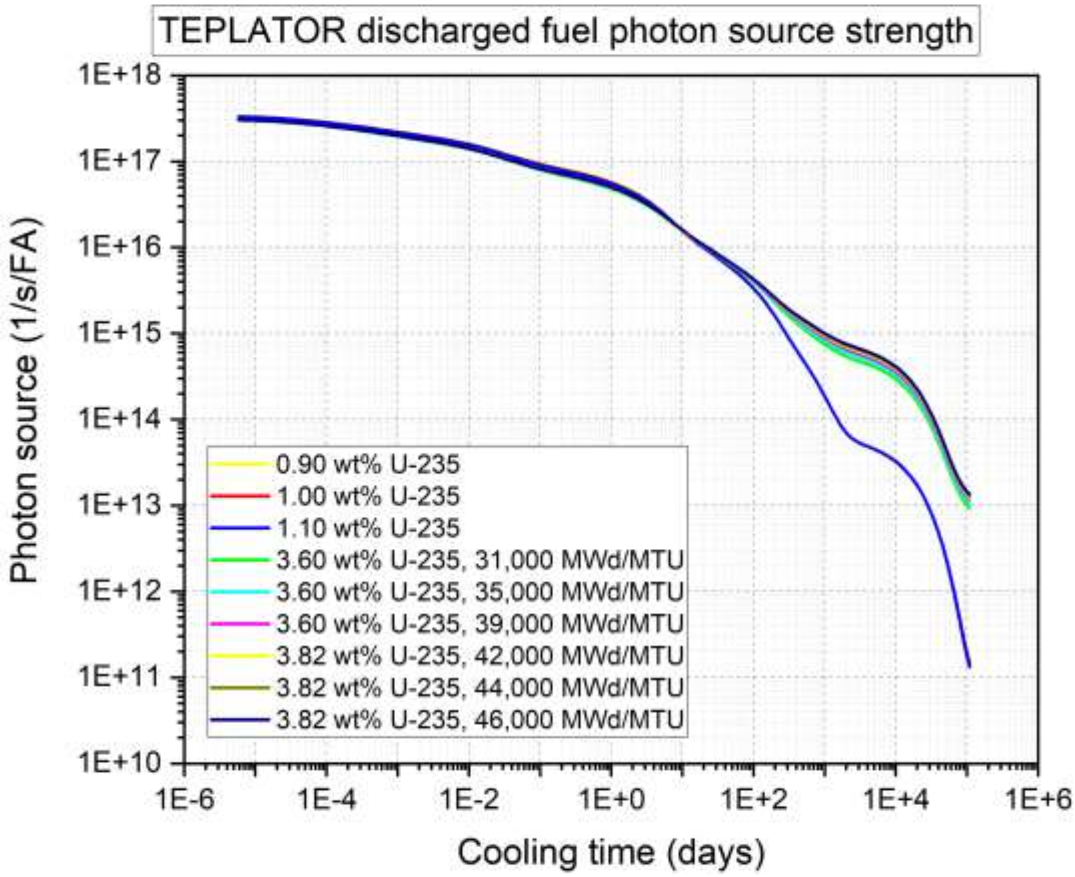

Fig. 2.5 TEPLATOR fuel photon source comparison

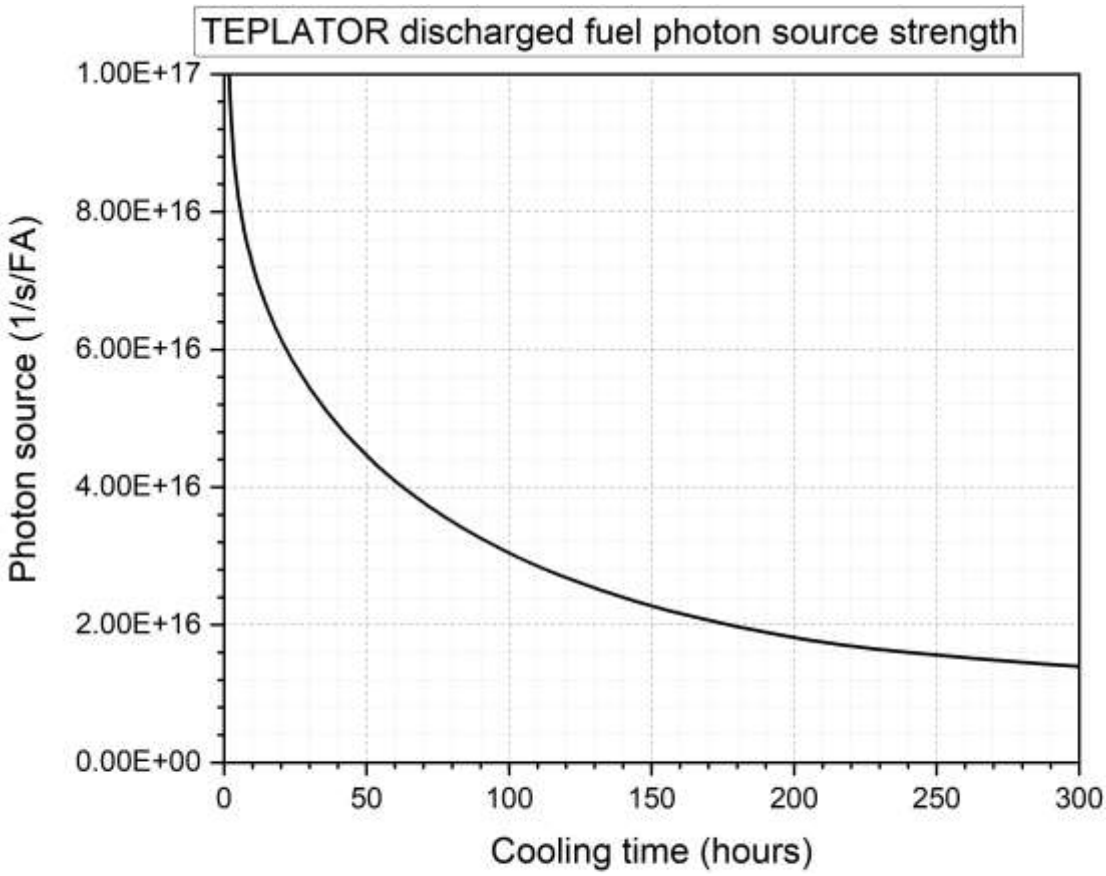

Fig. 2.6 TEPLATOR fuel photon source during fuel transfer

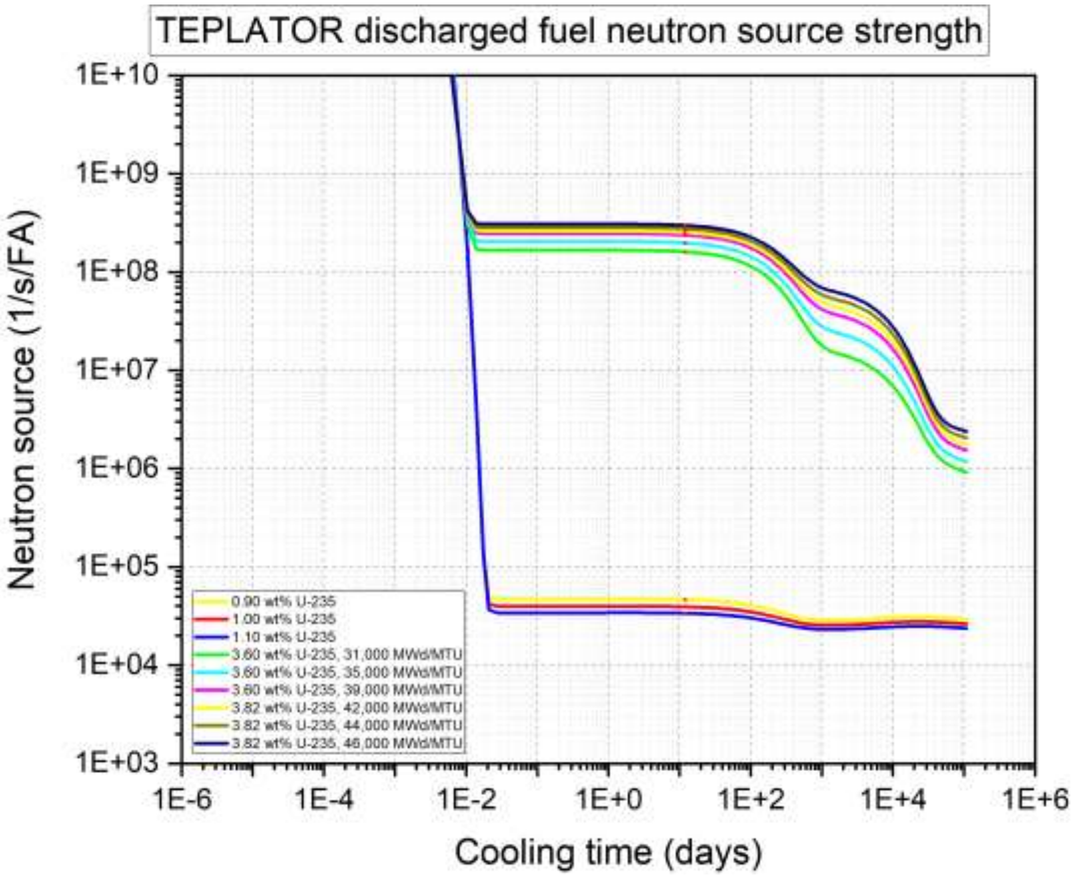

Fig. 2.7 TEPLATOR fuel neutron source comparison

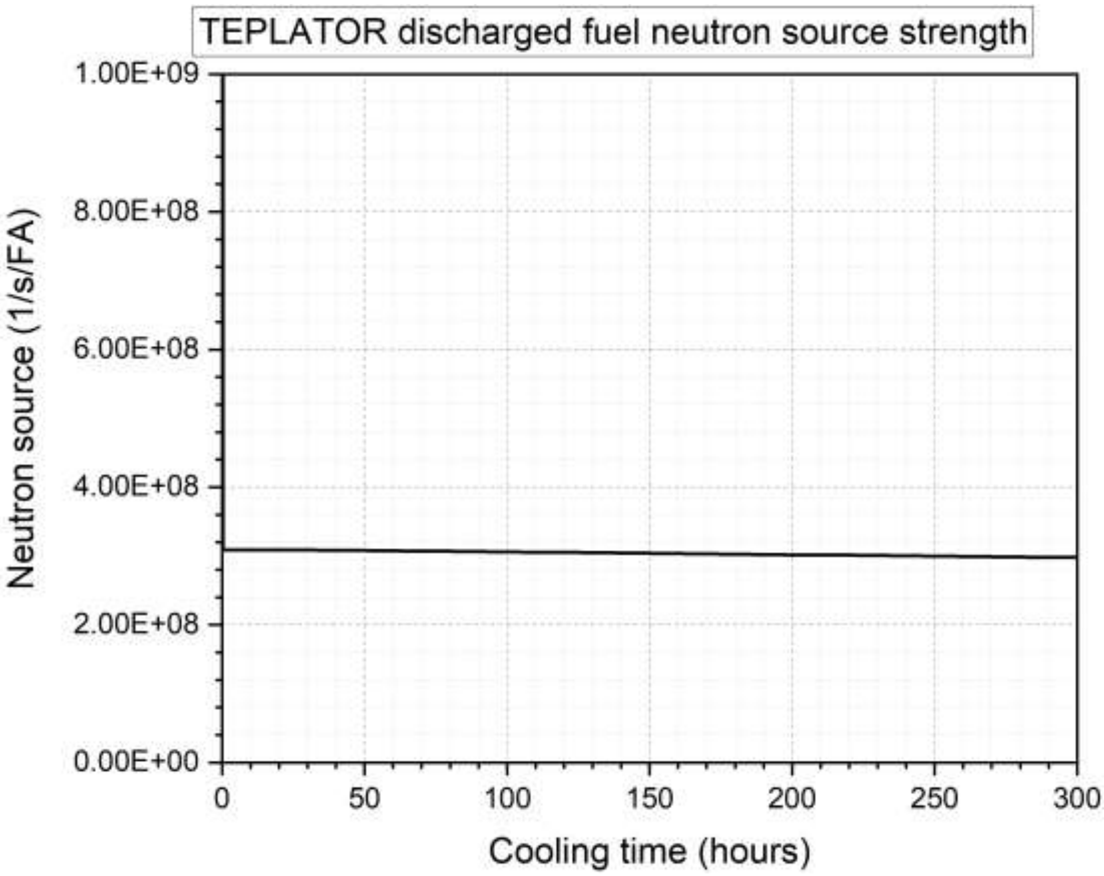

Fig. 2.8 TEPLATOR fuel neutron source during fuel transfer

3 Radiation shielding of refueling machine

The chapter includes the shielding calculation for the fuel assembly inside the refueling machine, considering various states during fuel management in the reactor and different target dose rates around the refueling machine.

3.1 Dose rate target values

A critical component of the TEPLATOR system is the refueling machine, which facilitates the safe and efficient transfer of nuclear fuel between the reactor core and the spent fuel storage pool. Given the operational complexities and the potential radiation exposure associated with this process, it is imperative to design effective radiation shielding to protect personnel and sensitive electronics.

This research report focuses on the radiation shielding analysis for the TEPLATOR refueling machine, utilizing the MCNP6.3 Monte Carlo code with ENDF/B-VII.1 nuclear data library. MCNP6.3 is renowned for its robust capabilities in simulating neutron and photon transport, making it an ideal tool for assessing the radiation environment and optimizing shielding configurations. The ENDF/B-VII.1 library provides comprehensive nuclear data essential for accurate neutron and photon dose rate calculations.

The shielding analysis addresses various operational states encountered during fuel management, from initial fuel loading to spent fuel transfer, ensuring that all potential radiation sources are accounted for. The goal is to achieve target dose rates that comply with safety standards, thereby ensuring the well-being of personnel and the functionality of electronic systems near the refueling machine. The outcomes of this analysis will inform the design and implementation of shielding materials and structures, contributing to the overall safety and efficiency of the TEPLATOR reactor system.

The target dose rates for personnel are set at 5 μSv/h, which is twice the limit for creating a controlled area. The target dose rate for electronics is 0.23 μSv/h, considering a 15 Gy limit for a 60-year operational lifetime with one month of exposure per year.

3.2 Shielding of one fuel assembly

In the first step, the shielding of a single fuel assembly is analyzed, which is then used as a conservative estimate for the refueling machine and is utilized to verify the shielding of the entire refueling machine model. Initially, the impact of water shielding was analyzed, as shown in Fig. 3.1 and Fig. 3.2, requiring 176 cm axially and 267 cm radially. Alternatively, in a dry state, the only solution is a combination of steel and polyethylene. Steel, as a material with heavy nuclei, effectively shields photons, while hydrogen-rich polyethylene moderates neutrons well and allows for effective neutron shielding. The results in Fig. 3.3 and Fig. 3.4show that 44 cm of steel followed by 14 cm of polyethylene are required in the radial direction. In the axial direction, 31 cm of steel without polyethylene is needed.

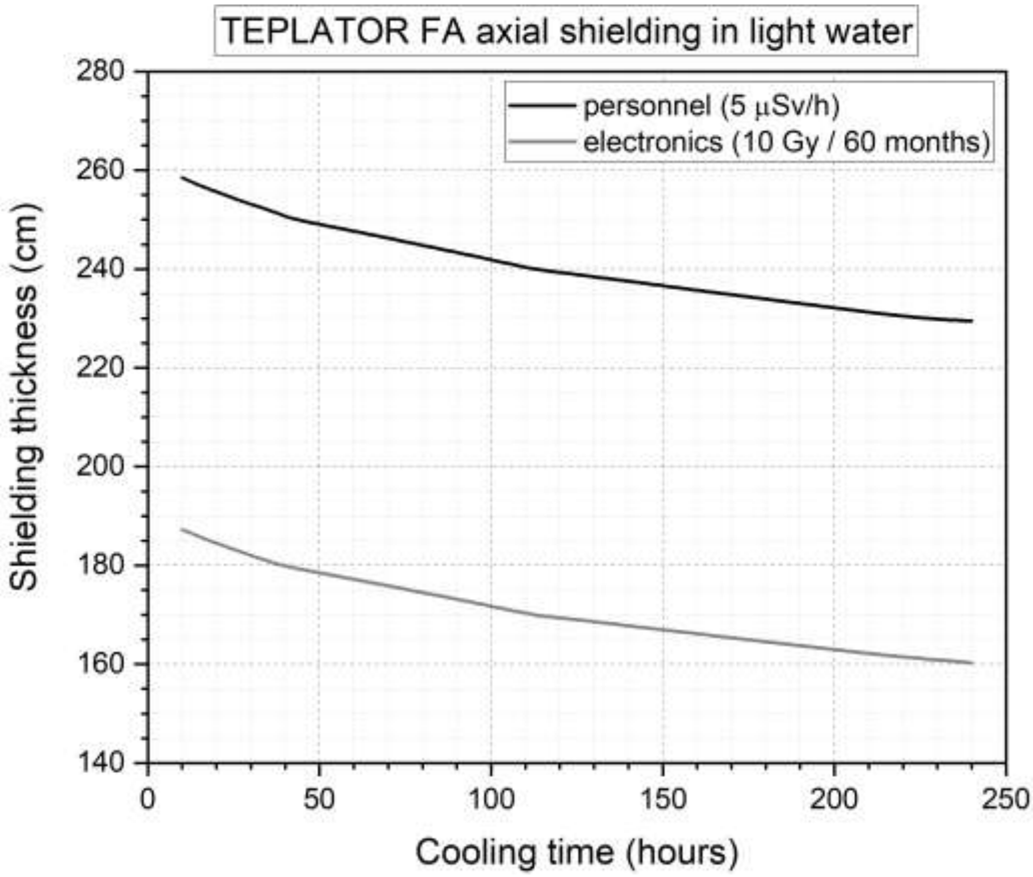

Fig. 3.1 TEPLATOR axial water shielding for 1 FA

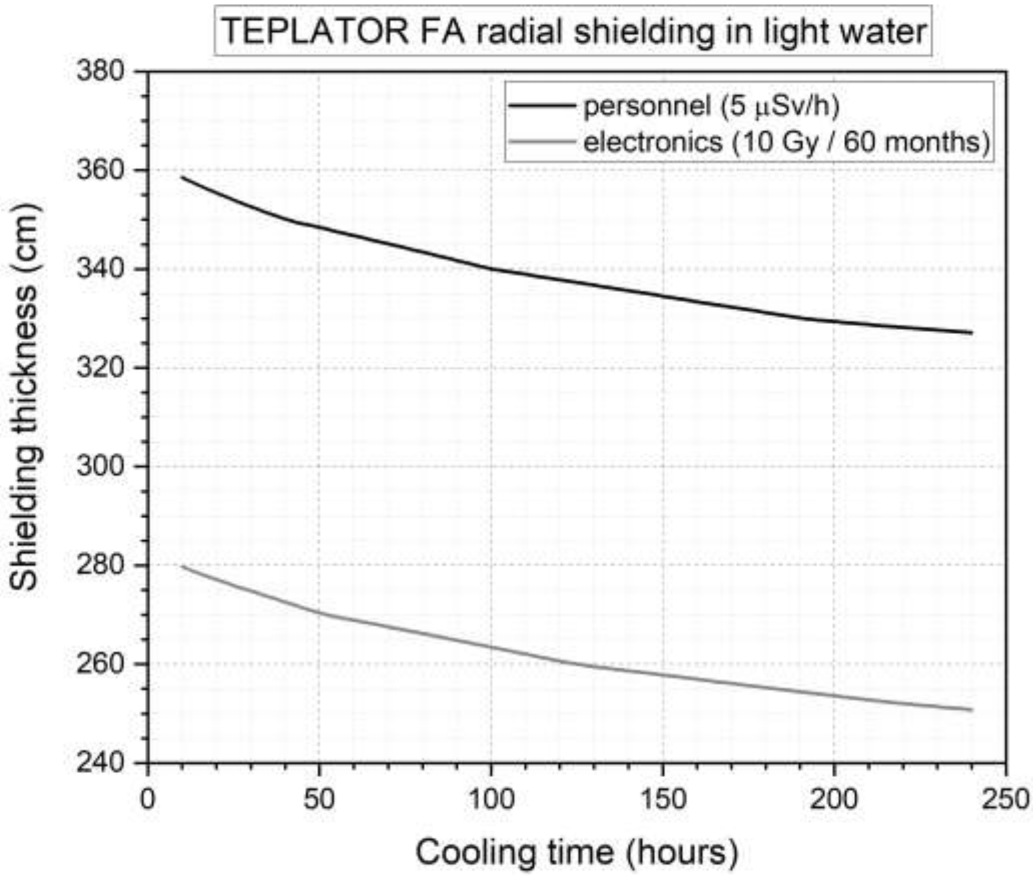

Fig. 3.2 TEPLATOR radial water shielding for 1 FA

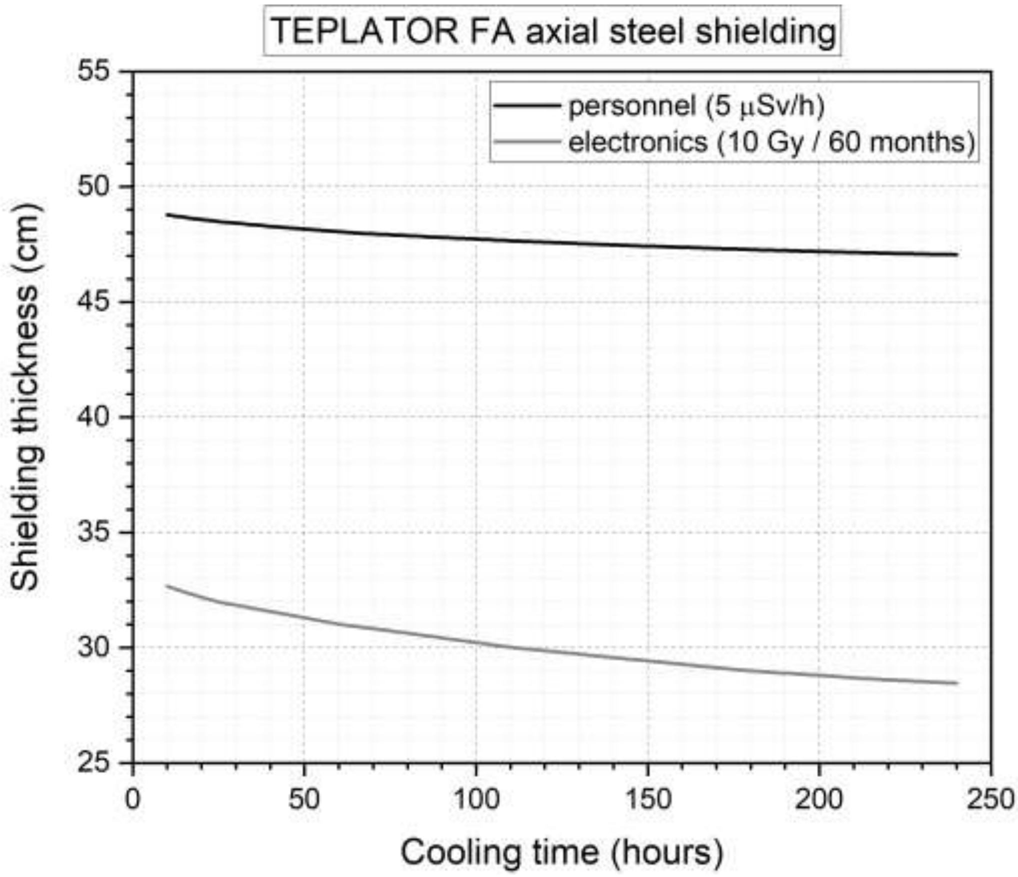

Fig. 3.3 TEPLATOR axial steel shielding for 1 FA

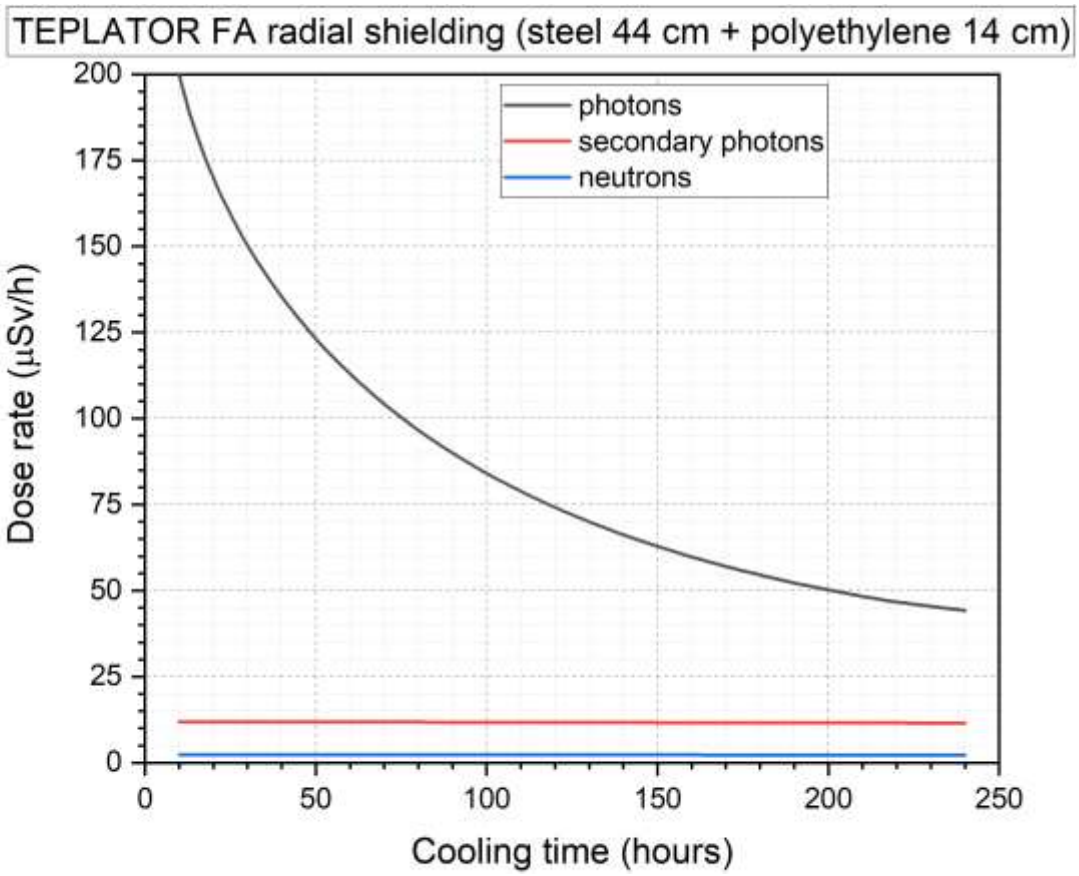

Fig. 3.4 TEPLATOR radial steel and polyethylene shielding for 1 FA

3.3 Refueling machine design

Fig. 3.5 provides a comprehensive overview of the refueling machine design. It illustrates the machine's overall structure and key components, highlighting the arrangement and integration of the various elements involved in the refueling process.

Fig. 3.6 shows the refueling machine design from the perspective of the yz plane. It details the vertical and lateral dimensions, emphasizing the spatial arrangement of the TEPLATOR reactor core (orange color) with refueling machine above, storage pool (blue color), and transport casks (green color).

Fig. 3.7 depicts the refueling machine design from the xz plane, focusing on the vertical and longitudinal dimensions with detail on the revolver tray.

Fig. 3.8 zooms in on the revolver tray, a crucial part of the refueling machine. The air gap and sealing position are highlighted.

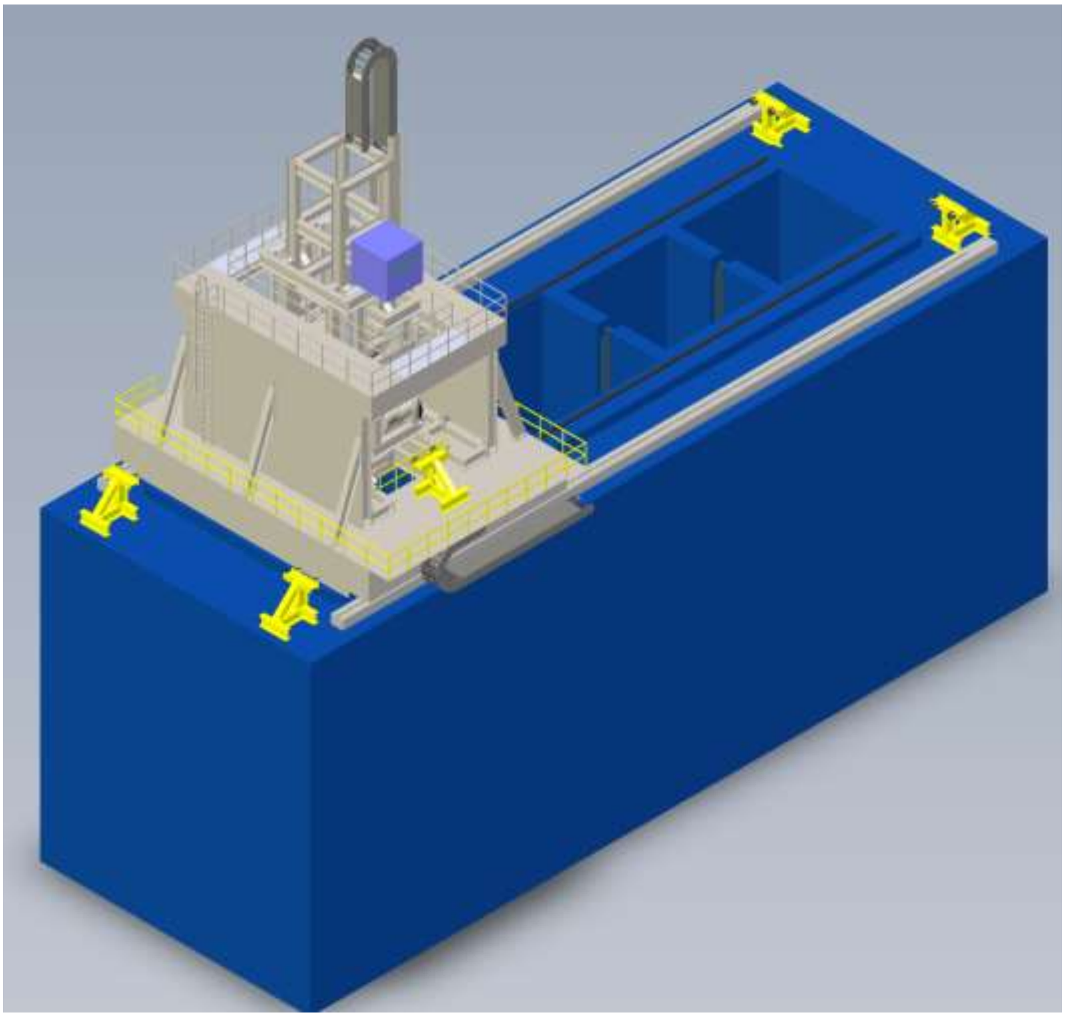

Fig. 3.5 Refueling machine design, overview

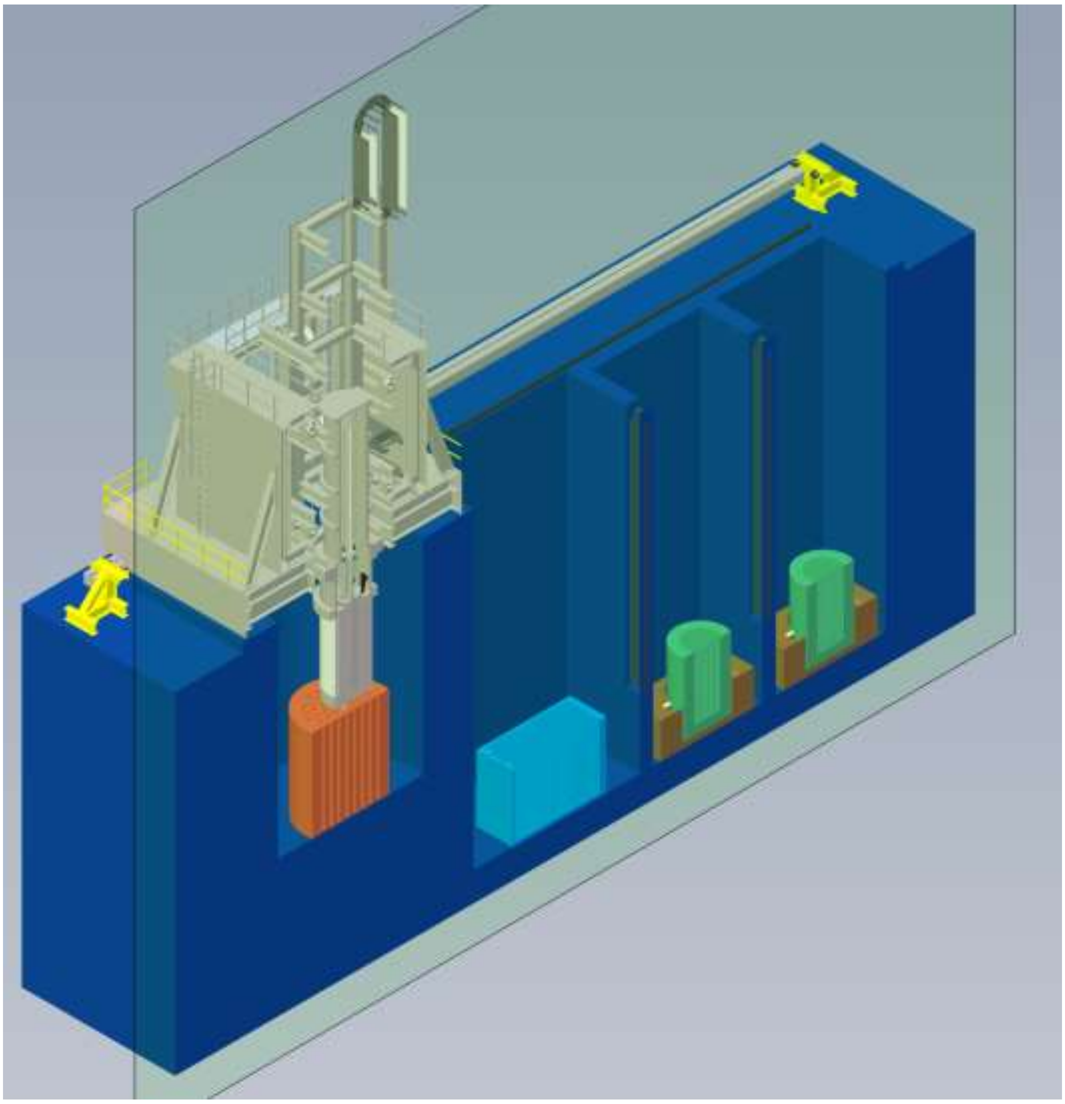

Fig. 3.6 Refueling machine design, view in yz plane

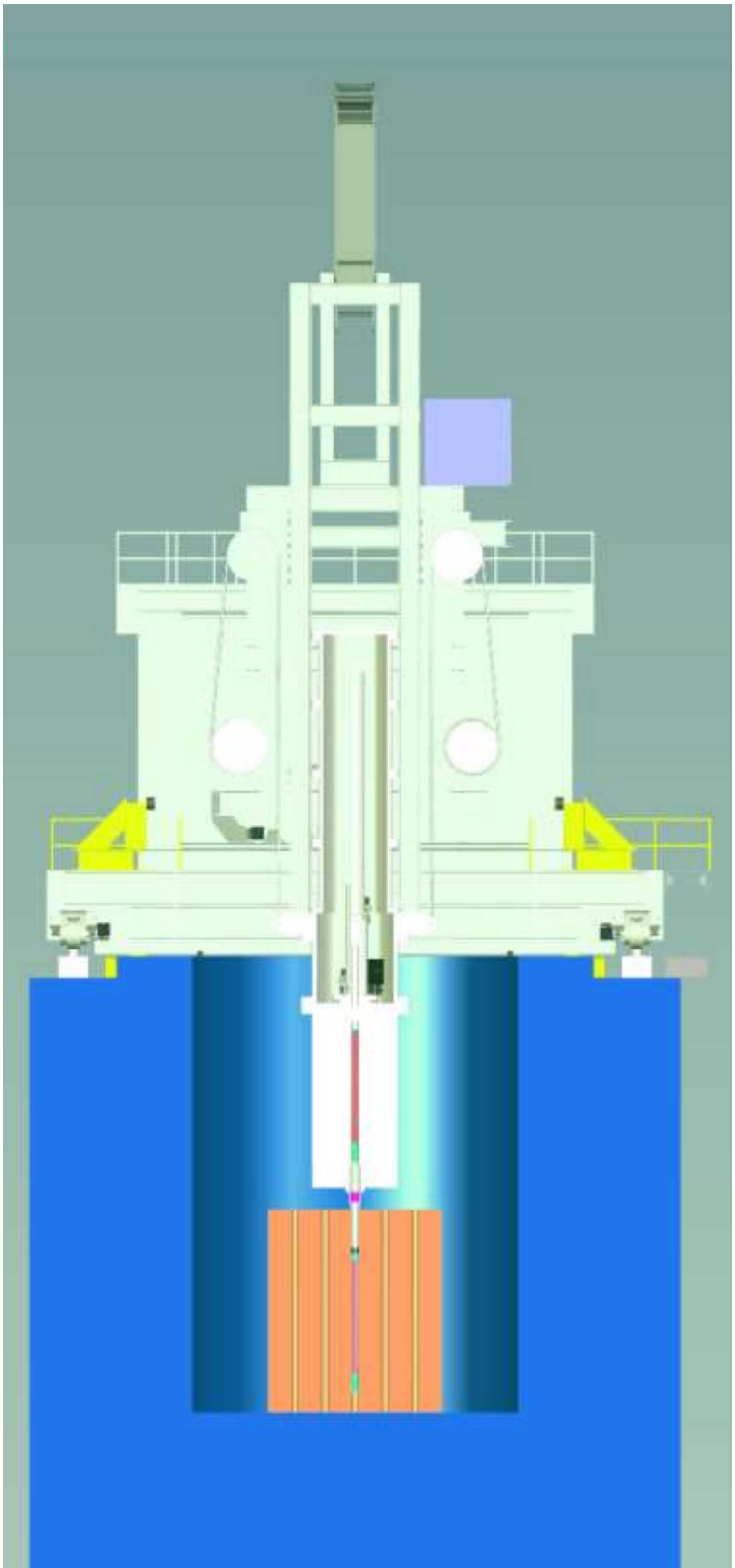

Fig. 3.7 Refueling machine design, view in xz plane

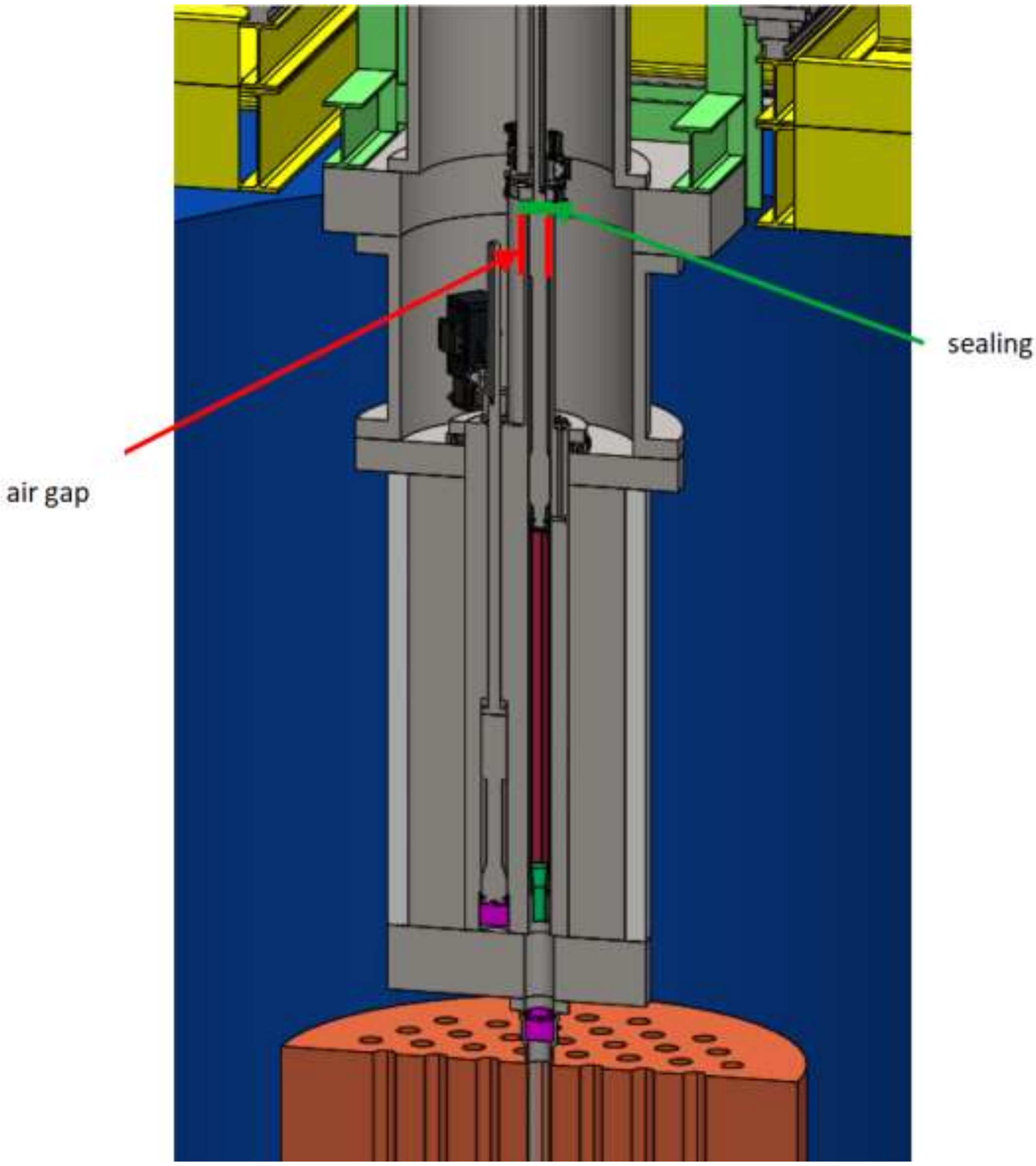

Fig. 3.8 Refueling machine design, detail of revolver tray

3.4 Shielding of refueling machine

In Fig. 3.9 and Fig. 3.10, a cross-section of the MCNP [3] computational model in the xy plane is shown, detailing the reactor core, above which the refueling machine is positioned. Fig. 3.11 presents a cross-section of the refueling machine in the xz plane. The total dose was calculated for three components: primary photons, secondary photons, and neutrons. The stricter limit is for the electronics monitored in the sealing area. Variations in the air gap thickness of 0 and 2 mm were considered, resulting in the finding that these variations in the sealing area affect the dose rate by only a few percent, making a 2 mm gap feasible.

Secondary photons from (n,γ) reactions have a negligible contribution to the total dose rate, primarily composed of photons and neutrons, as shown in Fig. 3.12 and Fig. 3.13. The axial profile of the dose rate along the revolver axis is illustrated in Fig. 3.14.

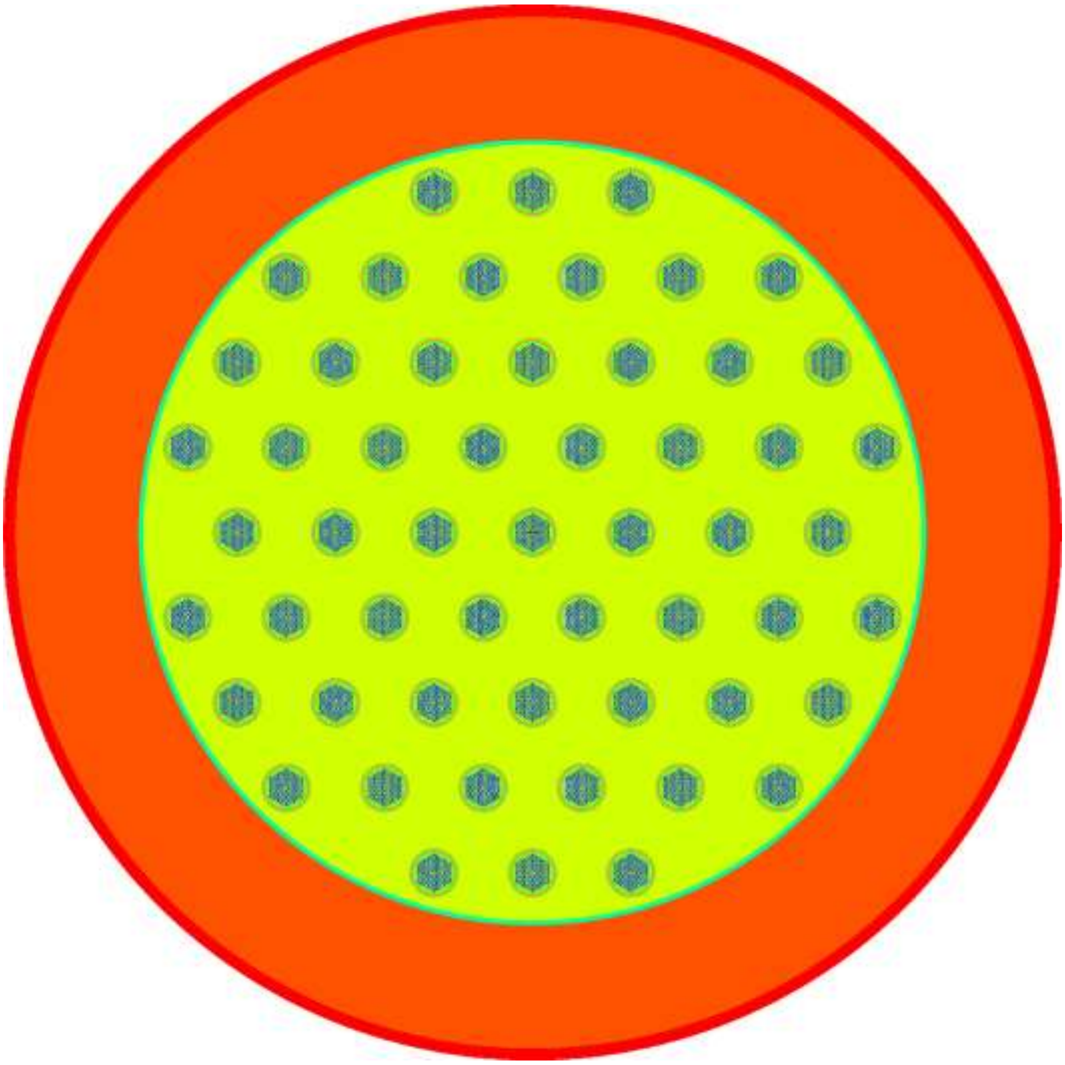

Fig. 3.9 Refueling machine design, MCNP model in xy plane

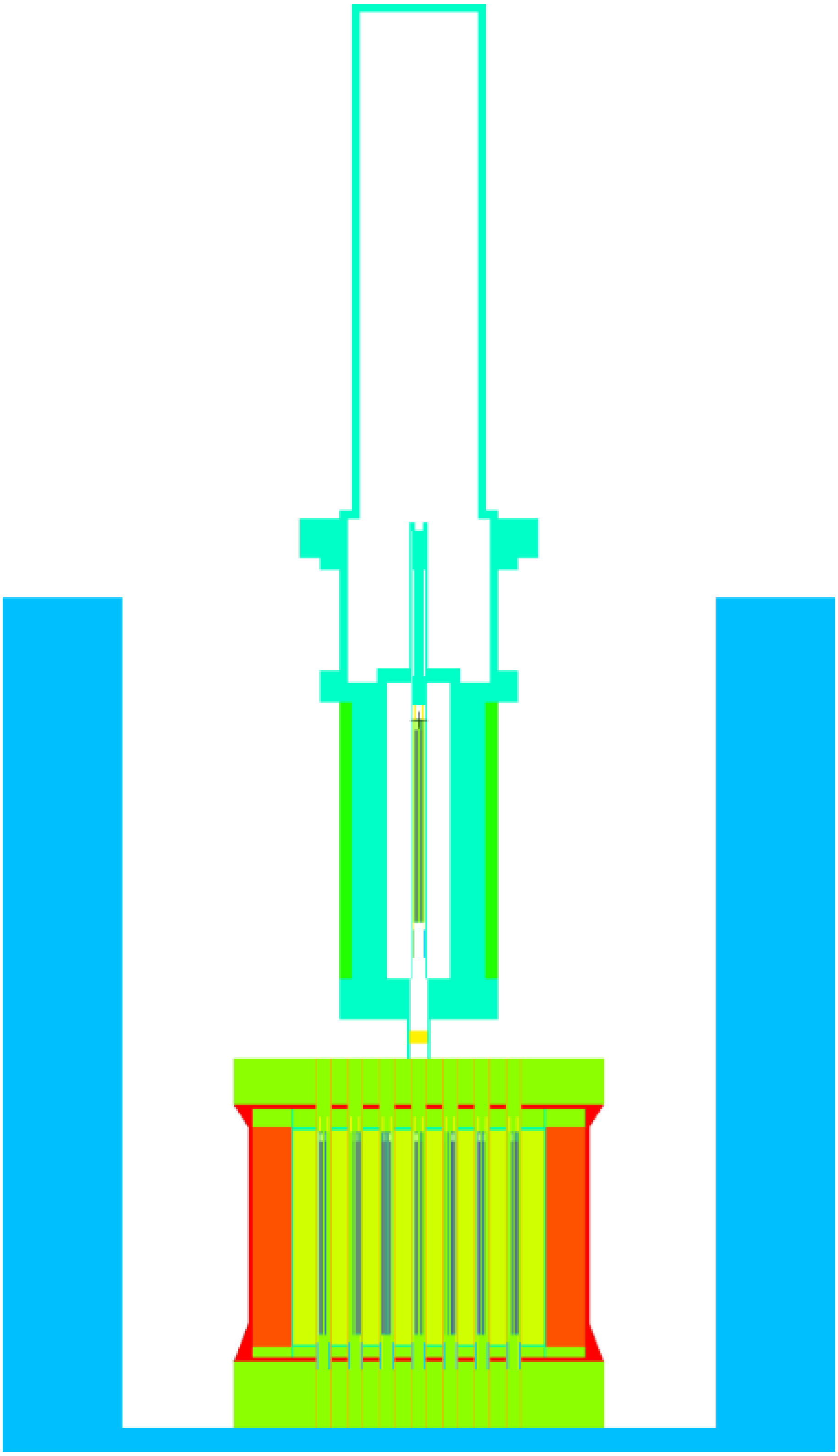

Fig. 3.10 Refueling machine design, MCNP model in xz plane

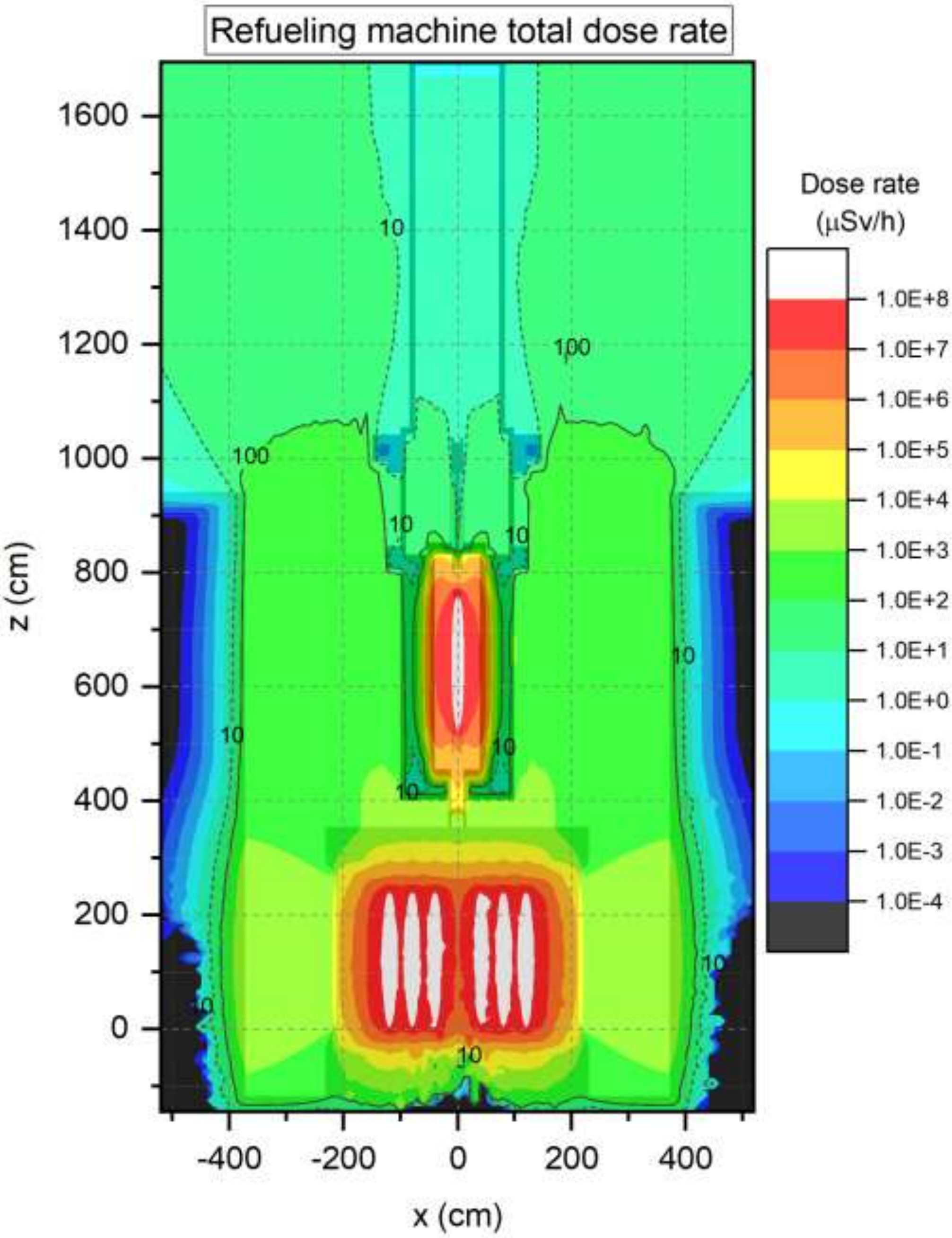

Fig. 3.11 Refueling machine design, total dose rate

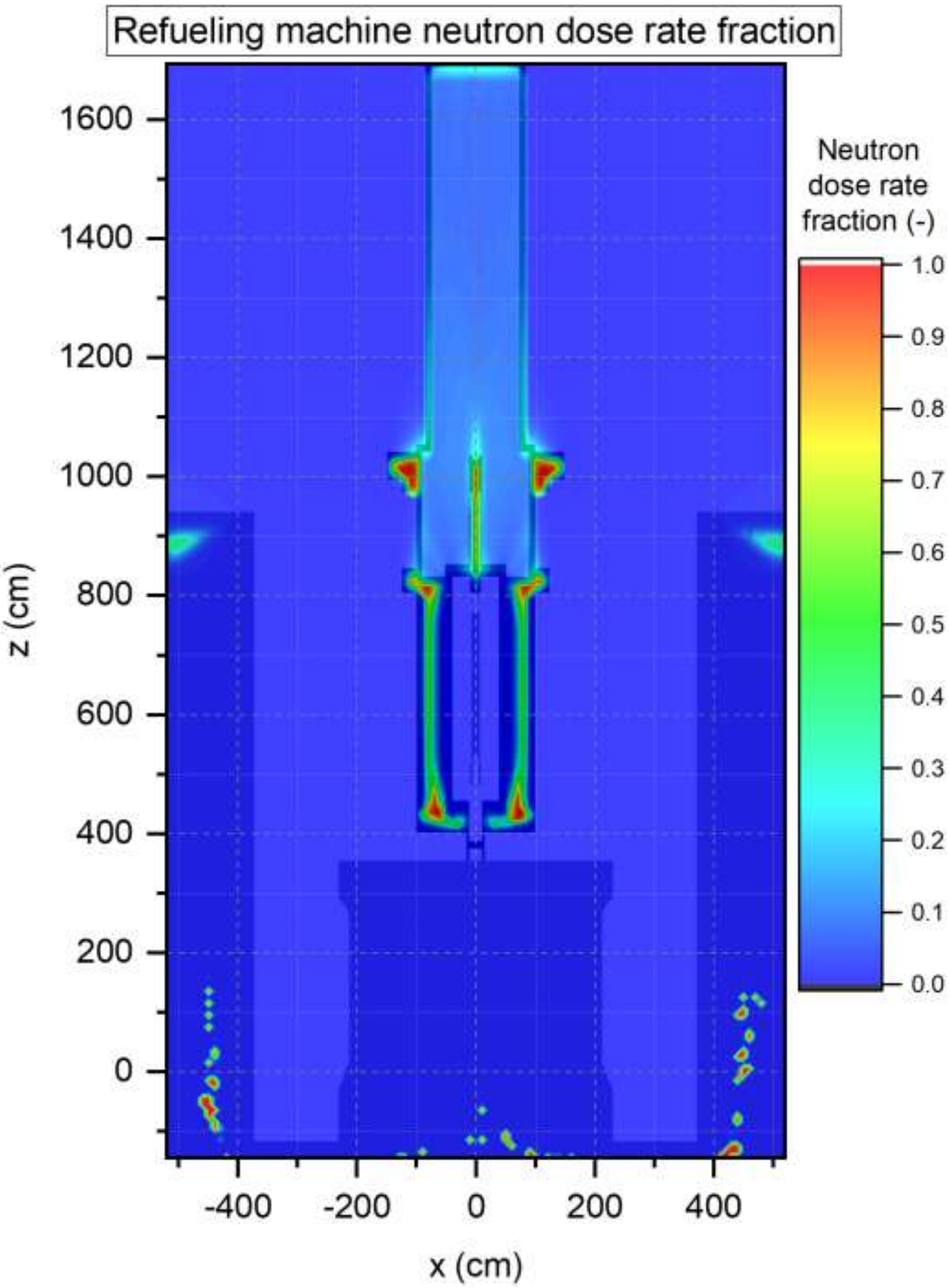

Fig. 3.12 Refueling machine design, neutron dose rate fraction

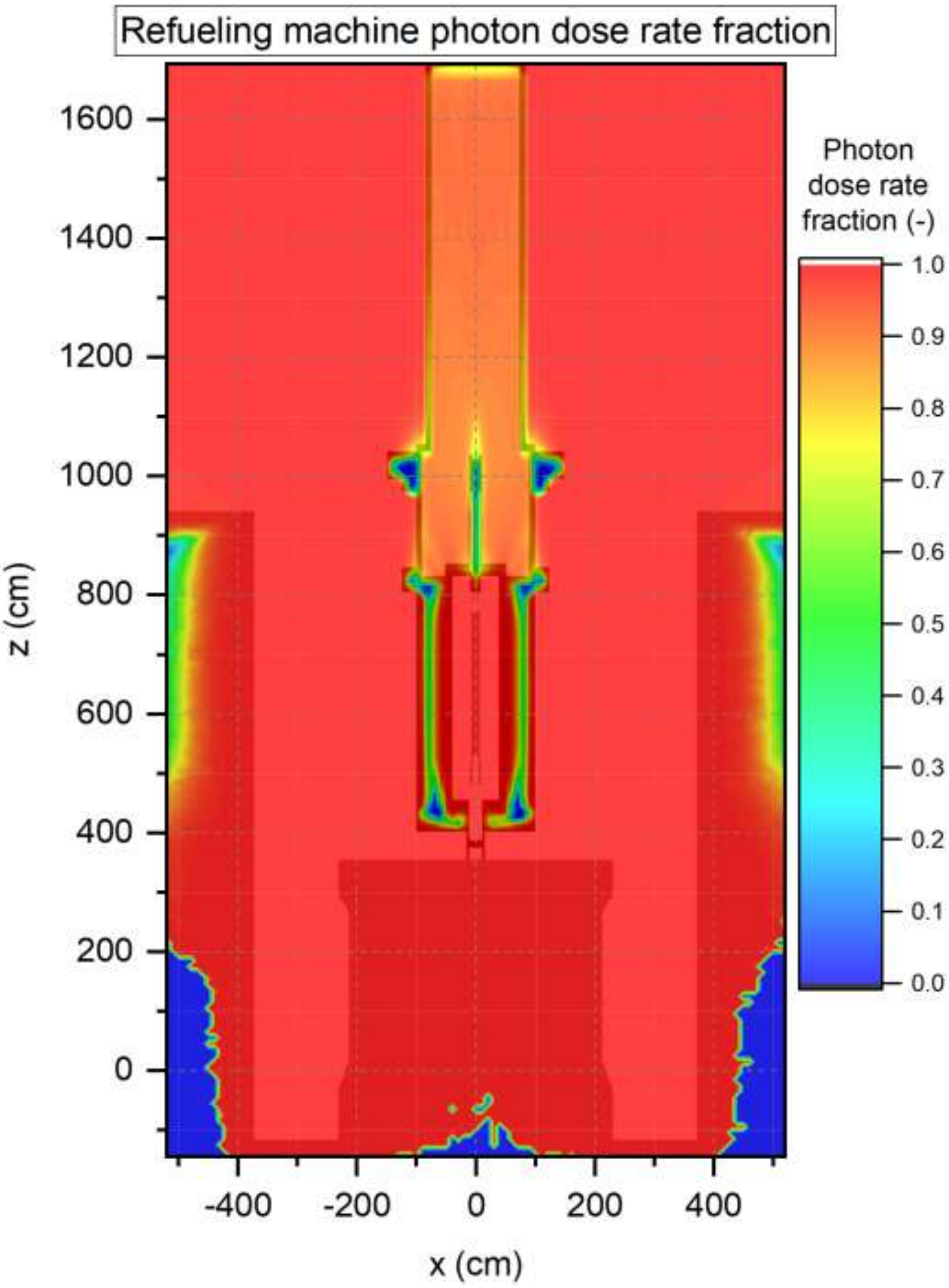

Fig. 3.13 Refueling machine design, photon dose rate fraction

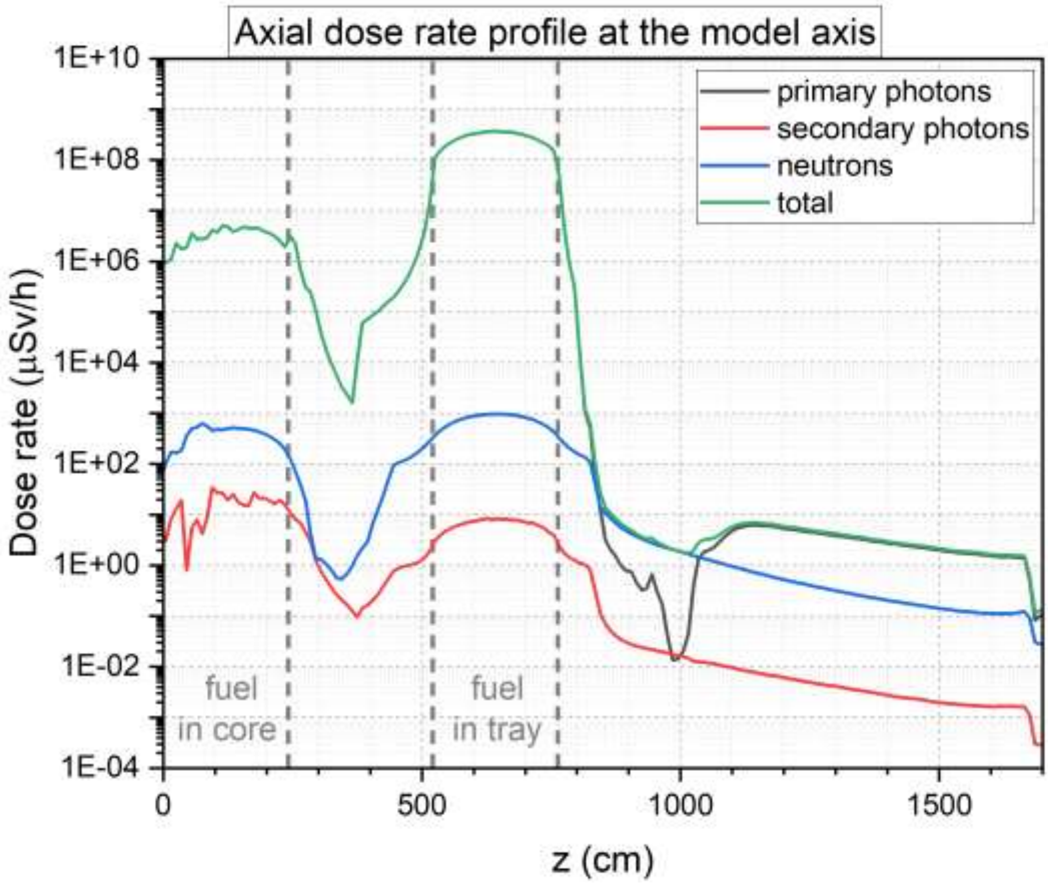

Fig. 3.14 Refueling machine design, axial dose rate

4 Conclusions

This report concentrated on the refueling machine, an essential component of the TEPLATOR reactor's operation. The refueling machine is crucial for the safe and efficient transfer of nuclear fuel between the reactor core, which operates in a heavy water environment, and the spent fuel storage pool, which uses light water as a coolant. Given the complexity of this process, thorough radiation shielding is necessary to ensure the safety of both personnel and the environment.

The report detailed the specifics of the shielding design, including the selection and arrangement of materials, the geometric configuration of the shielding, and the results of Monte Carlo simulations. These simulations were pivotal in determining the optimal shielding design of 44 cm of steel followed by 14 cm of polyethylene in the radial direction. And 31 cm of steel without polyethylene in the axial direction. These configurations provide the necessary protection to meet safety standards and regulatory requirements. The target dose rate for electronics is 0.23 Sv/h, considering a 15 Gy limit for a 60-year operational lifetime with one month of exposure per year.

This report contributes to developing safe and effective radiation shielding solutions for the TEPLATOR refueling machine.

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Revision history

Rev.	Chapter	Description of change	Date	Name
0	All	Document release	24.06.2024	M.Lovecký