Neutronic Characterisation of a Reconfigurable Reflector for the VERONICA Multipurpose Research Reactor

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ABSTRACT

The VERONICA project aims to develop a versatile, multipurpose research reactor capable of providing flexible irradiation conditions. This work evaluates a reconfigurable reflector concept using an OpenMC model of the VERONICA core and reflector. Two complementary studies were performed. First, a fully homogenised reflector was varied across the heavy-water–graphite–beryllium composition space. Beryllium-rich compositions increase the multiplication factor by up to 3–4 % relative to heavy water, while the plate power peaking factor ranges from 1.46 for pure graphite to 1.89 for pure heavy water. Heavy water preserves high thermal neutron flux deep into the reflector. Second, a partially reconfigurable reflector region was filled with different materials (void, aluminium, light water, graphite, or beryllium) to varying depths. Material selection changes the multiplication factor by up to -4 % and the power peaking factor by up to +18 % relative to the heavy-water reference, while the thermal-to-fast flux ratio in the reconfigurable region spans more than two orders of magnitude, from 3.0 (aluminium) to 356 (heavy water). These findings demonstrate the neutronic potential of a reconfigurable reflector for substantially expanding the irradiation capabilities of VERONICA.

1 INTRODUCTION

Research reactors support applications such as education and training, isotope production, neutron beam experiments, material irradiation and many others [1]. These applications often require different, and sometimes conflicting, neutron spectra. In conventional reactors with fixed reflectors, tailoring the spectrum usually requires neutron filters, which reduce the available irradiation volume and may perturb the core. A reconfigurable reflector could instead provide a controlled means of modifying the local neutron field, giving access to specific neutron spectra and large irradiation volumes, thereby increasing experimental flexibility.

The VERONICA project (Versatile European Reactor for Neutron Irradiation and Nuclear Research) [2] aims to address the decline in the number of European research reactors [3] by constructing a versatile, multipurpose research reactor. To support a broad range of applications, the concept includes a reflector whose composition can be modified to tailor the irradiation conditions. Similar ideas have been explored in the Brazilian RMB reactor, where a dedicated reflector region can be modified by inserting beryllium elements, primarily for fuel testing [4]. The proposal for the reconfigurable reflector in VERONICA goes beyond a single application and a single reflector material, aiming to maximise the variety of irradiation conditions available through the use of different materials in the reconfigurable reflector.

To assess the neutronic potential of this concept, an OpenMC model of the VERONICA core and reflector was developed. Two complementary studies were performed. First, a fully homogenised reflector was used to identify broad trends across the heavy-water–graphite–beryllium composition space. This idealised study is a physics-based parametric analysis rather than an engineering design. Second, a partially reconfigurable reflector region was filled with different materials to varying depths to evaluate their effects on core parameters and irradiation conditions. The OpenMC model is described in Section 2, followed by the homogenised reflector study in Section 3, the partially reconfigurable reflector study in Section 4, and the conclusions in Section 5.

2 OPENMC MODEL DESCRIPTION

OpenMC (version 0.14.0) [5] was used to model the VERONICA research reactor. The technical data and design characteristics were based on similar reactor concepts, such as OPAL [6], RA-10 [7], RMB [4], and JRTR [8].

A single fuel element is shown in Fig. 1. Each element consists of 21 U-Si-Al dispersion fuel plates with aluminium cladding. Three types of fuel element were used in the core loading pattern, differing in enrichment, uranium density, and the presence of cadmium wires (burnable absorbers). Fuel element parameters are shown in Table 1.

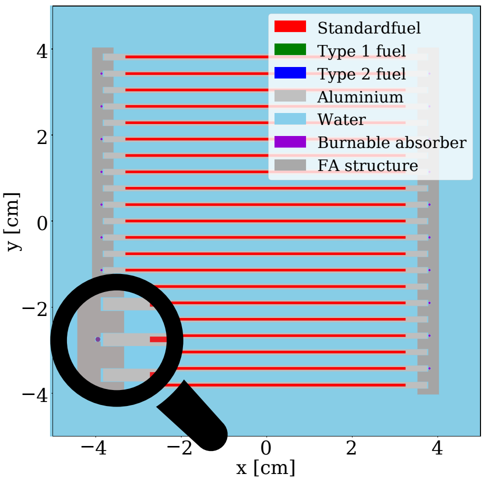

Figure 1: View of the standard fuel element.

Table 1: Fuel element types used in the core loading pattern.

Type	U^{235} enr. [%]	$\frac{m_U}{V_{meat}}$ [gU/cm^3]	Cd
Standard	19.82	4.77	Yes
Type 1	19.67	2.10	No
Type 2	19.75	3.79	Yes

The core layout is shown in Fig. 2. The loading pattern was defined according to the logic of the JRTR initial loading scheme [8], preserving high flux in the reflector. The irradiation positions inside the core were filled with aluminium placeholders to preserve the fast flux component.

In the reference configuration, the reflector is completely filled with heavy water. In the reflector phase-space study, the reflector material composition was varied among different homogeneous mixtures of heavy water ($\rho_{D_2O} = 1.1\frac{g}{cm^3}$), graphite ($\rho_C = 1.7\frac{g}{cm^3}$), and beryllium ($\rho_{Be} = 1.85\frac{g}{cm^3}$). For each composition, the reflector was treated as a fully homogenised region. The materials were mixed according to their volume fractions, using OpenMC's built-in `mix_materials` function.

For the reconfigurable reflector study, a 7×5 array of fuel-element-sized positions was defined within the reflector. The rows are numbered from 1 to 7, increasing with distance from the core. This region, highlighted by the dark mesh in Fig. 2, was filled with selected materials to evaluate their effect on key reactor parameters.

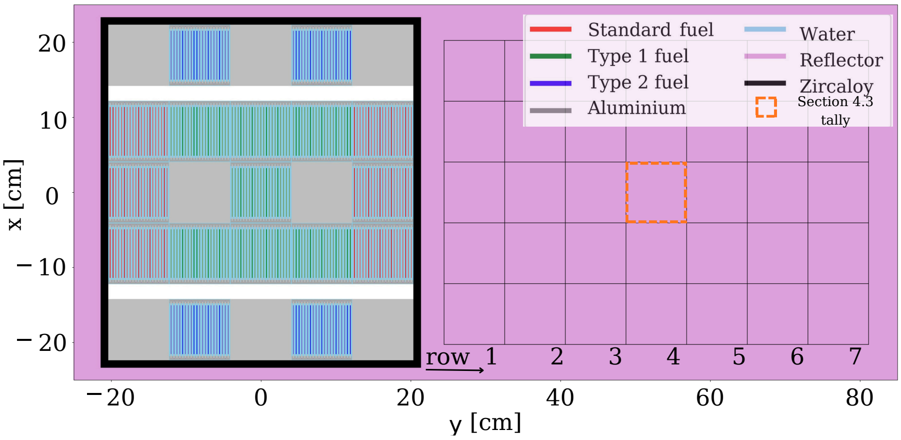

Figure 2: Top down view of the OpenMC reactor core and reconfigurable reflector region.

All calculations were performed using the ENDF/B-VIII.0 nuclear data library [9], including the thermal scattering law S(α, β). The fuel temperature was assumed to be 200°C, and the reflector temperature was set to 45°C. All calculations correspond to the "all-rods-out" condition at the beginning of the cycle with fresh fuel (zero burnup). The neutron flux was normalised to a reactor power of 10 W.

In the core, a mesh tally was defined at fuel plate resolution and used to evaluate the power distribution and plate power peaking factors. An additional mesh tally covering the full model geometry was defined to assess the effects of the reconfigurable reflector. All meshes used 640 logarithmically spaced energy bins between 10^{-4} eV and 10^{7} eV.

3 HOMOGENISED REFLECTOR PHASE-SPACE STUDY

A parametric study was carried out in which the composition of the entire reflector was varied across the heavy water–graphite–beryllium phase space. The aim of this study was not to produce a final engineering design, but rather to quantify how the reflector composition influences selected neutronic parameters. Findings from this study could guide reactor designers towards a feasible design. A pure heavy water reflector was used as the reference case.

3.1 Multiplication factor

The first quantity evaluated was the effective multiplication factor, k_{eff}, with the results shown in the left-hand graph in Fig. 3. The statistical standard deviation of the calculated points is 10 pcm.

Although the values of k_{eff} are relatively high, the objective of this study is not to determine the precise k_{eff} of a final reactor design, but to compare how different reflector compositions influence it. The observed trends between configurations are therefore more relevant than the absolute values themselves.

Pure heavy water and pure graphite reflector configurations yield relatively similar multiplication factors, whereas increasing the beryllium fraction produces a noticeable increase in k_{eff}. This trend is consistent with the favourable neutronic properties of beryllium as a reflector material, including its low neutron absorption, effective scattering characteristics, and potential contribution from $^{9}\text{Be}(n, 2n)$ reaction. Including some Be in the reflector, as is done at the JRTR, might therefore allow a more compact core with more efficient neutron economy.

3.2 Power peaking factors

The effect of reflector composition on the fuel plate power distribution was assessed using the plate power peaking factor, $F_P = \frac{P^{\mathrm{max}}_{\mathrm{plate}}}{\overline{P}_{\mathrm{plate}}}$, where $P^{\mathrm{max}}_{\mathrm{plate}}$ is the highest power of any fuel plate and $\overline{P}_{\mathrm{plate}}$ is the average power of all fuel plates. The corresponding phase-space map is shown in the graph on the right in Fig. 3. The absolute uncertainty of each plotted value is 0.003. Markers denote the values at compositions calculated with OpenMC, while the continuous contours were obtained by linear interpolation and serve as a visual guide. The highest power peaking factors occur with a heavy water reflector, while the lowest values are found for graphite reflectors. Core power peaking maps for the cases with the highest and lowest values of F_P are presented in Fig. 4.

A heavy water reflector returns a larger fraction of well-thermalised neutrons to the core periphery, increasing fission rates in the outer fuel plates and thus raising the plate power peaking factor. In contrast, graphite causes a smaller average energy loss per collision, so reflected neutrons have higher energies and can penetrate further into the core before inducing fission. This results in lower power peaking factors.

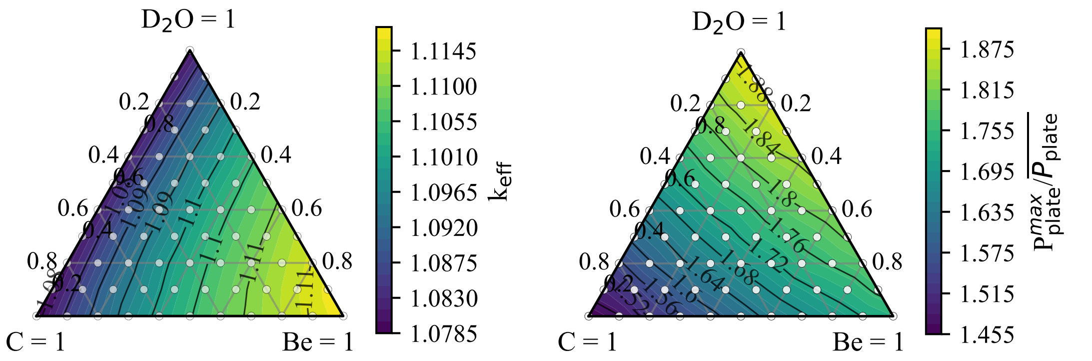

Figure 3: Effect of reflector composition on the effective multiplication factor, k_{eff} (left), and the fuel plate power peaking factor, F_P (right).

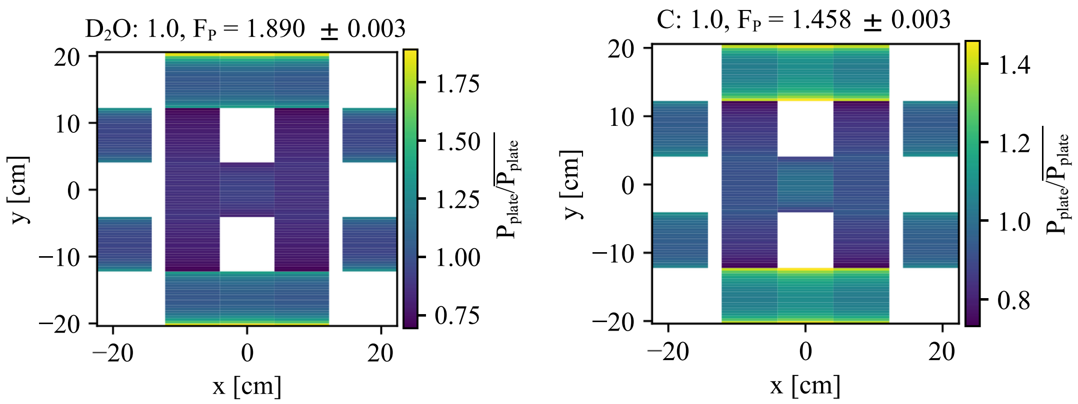

Figure 4: Core maps of normalize fuel plate power for the reflector compositions producing the highest (left) and lowest (right) plate power peaking factors.

4 PARTIALLY RECONFIGURABLE REFLECTOR

This section evaluates a partially reconfigurable reflector in which selected rows of the heavy-water reflector are replaced with alternative materials. The analysis considers three effects: changes in multiplication factor and fuel plate power peaking, the dependence of core coupling on the number of filled rows, and the evaluation of irradiation conditions that a reconfigurable reflector may provide.

4.1 Effect on multiplication factor and power peaking

The entire reconfigurable region was filled with material i, being either void, aluminium, H_2O, graphite, or beryllium, with D_2O used as the reference case. Figure 5 shows the corresponding relative changes in the effective multiplication factor, $\Delta k_{\text{eff}} = \frac{k^i_{\text{eff}}}{k^{D_2O}_{\text{eff}}} - 1$, and the plate power peaking factor, $\Delta F_P = \frac{F^i_{\text{P}}}{F^{D_2O}_{\text{P}}} - 1$.

Replacing D_2O with void or aluminium reduces k_{eff} because these configurations reflect neutrons poorly, resulting in a lower neutron return to the core. The decrease observed for H_2O is primarily attributed to its greater neutron absorption compared with D_2O. Beryllium produces a small increase in k_{eff}, consistent with the trend observed in the homogenised reflector study.

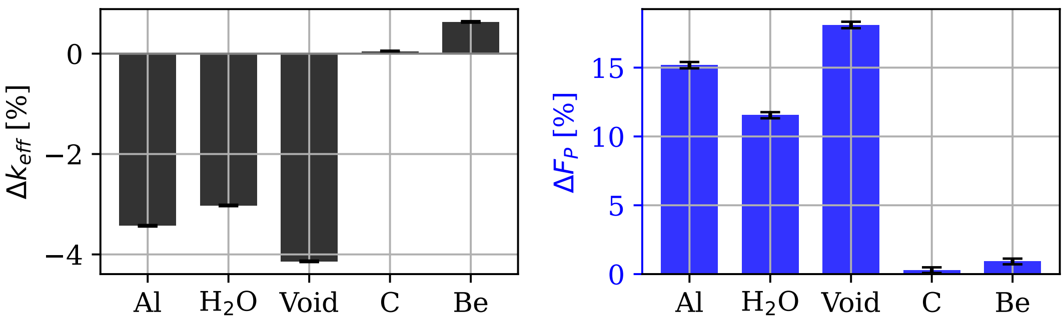

Figure 5: Relative changes in multiplication factor, Δk_{eff}, and plate power peaking factor, ΔF_P, for different materials in the reconfigurable reflector. The reference case is the full D_2O reflector.

Figure 6 shows the relative change in the plate power, $P(i)/P(D_2O) - 1$, for the void and beryllium cases. The largest changes occur in the fuel elements closest to the reconfigurable region, producing a tilt in the core power distribution. Materials that reduce k_{eff} decrease the power near the reconfigurable region, leading to an increase on the opposite side of the core, while beryllium produces the opposite effect. This loss of power symmetry should be considered in loading-pattern optimisation and burnup calculations, especially if the reflector configuration is changed frequently. A mirrored reconfigurable region could reduce the tilt, but would also reduce the reflector volume available for applications such as isotope production or silicon doping.

4.2 Influence of reconfigurable reflector depth on the core

Figure 7 shows how the multiplication factor depends on the number of filled rows in the reconfigurable region. For filling depth n, the first n rows adjacent to the core were filled with

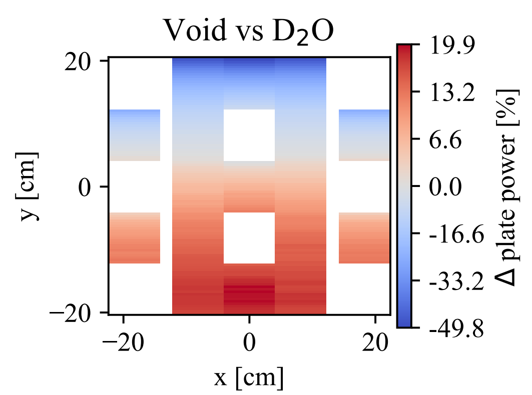

Figure 6: Change in plate power for different materials in the reconfigurable reflector with respect to the reference D_2O case: void (left), Be (right).

the selected material, while the remaining positions were left void. For aluminium and H_2O, k_{eff} changes only weakly after the first few rows are filled, although for different physical reasons. Aluminium is relatively transparent to neutrons, so additional filled rows have little effect on the spectrum or direction of the neutron field. In H_2O, by contrast, the short neutron mean free path strongly attenuates the influence of material placed farther from the core.

This behaviour is particularly important for a D_2O reflector, where the longer neutron mean free path allows changes far from the core to still affect k_{eff}. As shown by the derivative in Fig. 7, D_2O and C are the materials whose influence on k_{eff} extends furthest from the core. Introducing a suitable buffer material, such as H_2O in a reconfigurable reflector, could therefore reduce the impact of experiments on the reactor core.

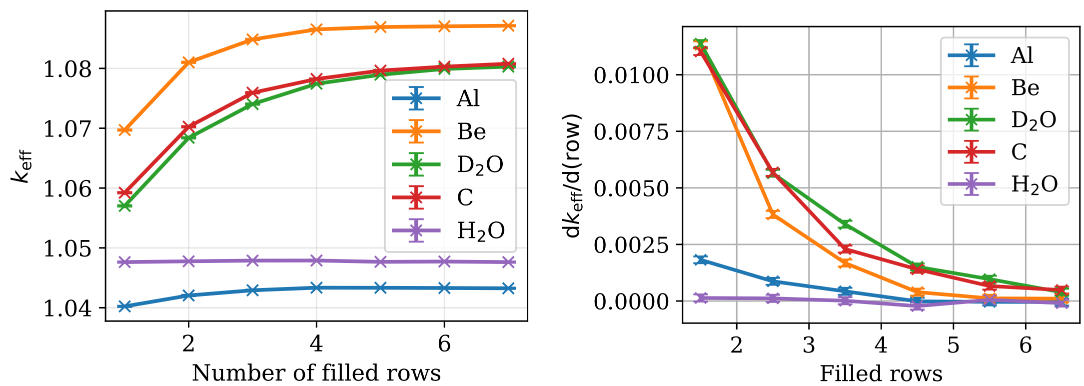

Figure 7: Dependence of k_{eff} on the number of filled rows in the reconfigurable reflector for different materials (left) and its derivative (right).

4.3 Neutron flux spectra achievable with the reconfigurable reflector

A key advantage of a reconfigurable reflector is its ability to provide neutron spectra that cannot be achieved with a homogeneous reflector.

The dependence of the neutron flux spectrum on material choice and the number of filled rows n is shown in Fig. 8. The left plot presents neutron flux spectra at the centre of the reconfigurable region (row 4, column 3) for selected materials and insertion depths. The spectra differ substantially, demonstrating that the spectrum can be effectively modified by both the amount and type of inserted material. Aluminium reduces moderation and therefore preserves the fast and epithermal flux. The other materials produce different spectral shapes, confirming that the reflector configuration offers a means of tailoring the neutron spectrum.

The right-hand plot in Fig. 8 summarises this behaviour using the thermal-to-fast flux ratio $\frac{\Phi_{\mathrm{th}}(E<0.625\ \mathrm{eV})}{\Phi_{\mathrm{f}}(E>100\ \mathrm{keV})}$ at the centre of the reconfigurable region (row 4, column 3). Even with the limited set of materials considered here, the ratio varies by more than two orders of magnitude. The lowest values are obtained for aluminium and H_2O configurations, while D_2O and Be produce more thermalised spectra. A drop in $\frac{\Phi_{\mathrm{th}}}{\Phi_{\mathrm{f}}}$ occurs at $n = 4$ for all materials except D_2O. This occurs because the material at the tally positions changes from void to inserted material, altering the flux distribution, especially the thermal flux. The particularly strong decrease for H_2O results from its relatively short neutron mean free path and high absorption cross section compared with heavy water, which does not exhibit such a drop in thermal flux due to its longer neutron mean free path and lower absorption cross section.

These results show that a reconfigurable reflector can substantially broaden the range of achievable neutron spectra. Future work should therefore investigate mixed-material configurations and optimisation methods to identify reflector layouts that satisfy specific irradiation requirements.

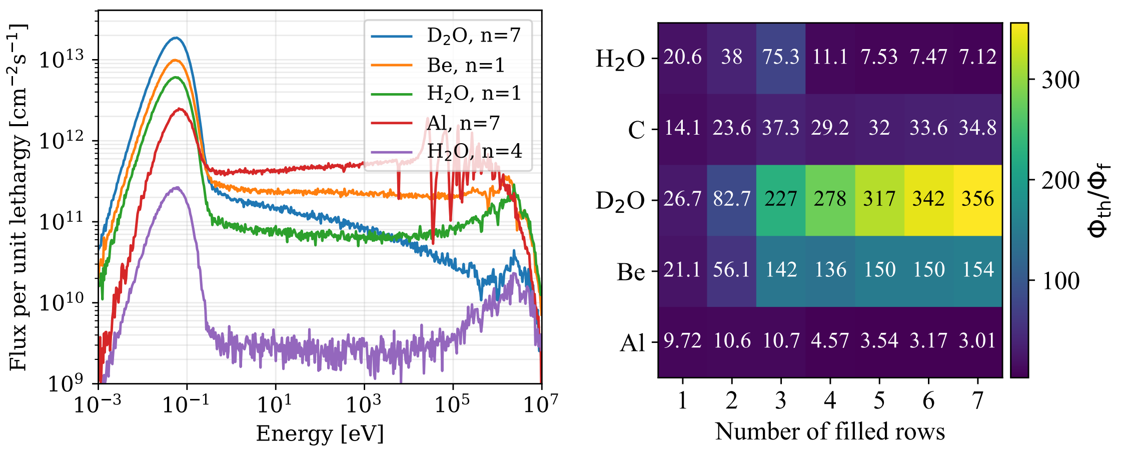

Figure 8: Neutron flux lethargy spectrum for selected materials filled to different depths n (left), and thermal-to-fast neutron flux ratio for all calculated fillings of the reconfigurable reflector (right) at the centre of the reconfigurable reflector.

5 CONCLUSION

The homogenised reflector study showed that no single reflector material is optimal for all performance indicators. Beryllium-rich compositions produced the highest multiplication factors, exceeding the heavy water reference by 3–4 %, while graphite yielded the lowest plate power peaking factor (1.46, compared with 1.89 for pure heavy water) and heavy water provided the strongest thermalisation and the longest neutron transport in the reflector. These trends provide the physical basis for interpreting the partially reconfigurable cases and offer insight into designing the reflector of the VERONICA multipurpose reactor.

The partially reconfigurable reflector study demonstrated the main benefit of the proposed concept. Replacing the heavy water in the reconfigurable region with another material decreases

k_{eff} by up to 4 % for the void configuration and increases F_P by up to 18 %, introducing a tilt in the core power distribution. This effect should be considered in loading-pattern optimisation and burnup calculations, especially if the reflector configuration is changed frequently during operation. At the same time, some materials can be used to reduce the effects of experiments behind the reconfigurable reflector on the core: materials with short neutron mean free paths, such as light water, provide a possible means of decoupling experiments from the reactor core.

Most importantly, the reconfigurable reflector substantially expands the achievable neutron flux spectra. Even the limited set of single-material configurations studied here varied the thermal-to-fast flux ratio in the reconfigurable region by more than two orders of magnitude, from 3.0 for aluminium to 356 for heavy water. The reflector configuration can therefore serve as an additional design variable for tailoring irradiation conditions, rather than only as a passive component surrounding the core. The results support the reconfigurable reflector as a promising approach to increasing the versatility of the VERONICA reactor concept.

Future work should investigate mixed-material reflector configurations, optimisation methods for targeting specific neutron spectra, and the impact of reflector changes on other irradiation positions, including isotope production and neutron transmutation doping of silicon. Burnup calculations will also be required to assess the operational consequences of changing reflector configurations over the fuel cycle.

REFERENCES

[1] IAEA, "Applications of Research Reactors", Nuclear Energy Series No. NP-T-5.3, IAEA, Vienna (2014).

[2] Jožef Stefan Institute, VERONICA - Versatile European Reactor for Neutron Irradiation and Nuclear Research, `https://veronica.ijs.si/`, 29. 7. 2026.

[3] A. Pungerčič et al., "European research reactor strategy derived in the scope of the towards optimized use of research reactors (TOURR) project", Ann. Nucl. Energy, 211, 110963 (2025).

[4] J. M. Tuñón et al., "Neutronic Design of the RMB Research Reactor", 16th International Group on Research Reactors Meeting, Bariloche, Argentina (2014).

[5] P. K. Romano et al., "OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development," Ann. Nucl. Energy, 82, 90–97 (2015).

[6] IAEA, "Research Reactor Benchmarking Database: Facility Specification and Experimental Data", Technical Reports Series No. 480, IAEA, Vienna (2015).

[7] H. Blaumann, "RA-10: A New Argentinian Multipurpose Research Reactor", International Conference on Research Reactors: Safe Management and Effective Utilization, Rabat, Morocco (2011).

[8] M. K. Jaradat et al., "Verification of MCNP6 model of the Jordan Research and Training Reactor for calculations of neutronic parameters", Ann. Nucl. Energy, 96, 96–103 (2016).

[9] D. A. Brown et al., "ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data", Nucl. Data Sheets, 148, 1–142 (2018).