# Progress in the Technical Design of the VERONICA (Versatile European Reactor for Neutron Irradiation and Nuclear Research) Research Reactor

**A. Pungerčič[1,2], B. Levpušček[1,2], K. Ambrožič[1,2], V. Radulović[1,2], I. Tiselj[1,2], N. Thiollay[3], C. Destouches[3], R. Jacqmin[3], X. Wohleber[4], A. Lyoussi[3], J. F. Villard[3], C. Vaglio-Gaudard[3] and L. Snoj[1,2]**

[1]"Jožef Stefan" Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia

[2]Faculty of Mathematics and Physics, University of Ljubljana, Jadranska ulica 19, 1000 Ljubljana, Slovenia

[3]CEA, DES, IRESNE, Cadarache F-13108 Saint-Paul-Lez-Durance, France

[4]CEA, DRF, IRFU, F-91190 Saclay, France

anze.pungercic@ijs.si

## ABSTRACT

Nuclear research reactors (RR) are essential facilities for advancing nuclear science and technology, educating students and nuclear professionals, producing medical isotopes, and testing future energy technologies such as fusion, small modular reactors (SMRs) and Generation IV reactors. As the European RR fleet continues to age and shrink, while interest in nuclear energy and the demand for RR services keep growing, the VERONICA (Versatile European Reactor for Neutron Irradiation and Nuclear Research) project — a collaboration between the Jožef Stefan Institute (JSI) and CEA — proposes a new dual-core research reactor facility in Slovenia, comprising a Multi-Purpose Research Reactor (MPRR) and a Zero-Power Reactor (ZPR). Building on the technical-requirements analysis reported previously, in which more than 35 identified MPRR applications and 15 ZPR applications were formalized into a three-dimensional utilization phase-space of neutron flux, spectrum and temperature, this paper reports on the progress made in the technical design of both reactors and presents an initial computational characterization of the MPRR. The design description covers the MPRR core and heavy-water reflector concept, the spectrum-shifting device, the dedicated multiphysics experimental loop for coupled neutronics–thermal-hydraulics investigations, the high- and low-temperature irradiation ports, and other irradiation and beam positions, together with the flexible-core, fuel-loading and benchmarking capabilities of the ZPR. Preliminary Monte Carlo neutron transport calculations for a first, 17-fuel-element MPRR core loading pattern are then used to provide first estimates of the thermal, epithermal and fast neutron flux levels achievable in the core, reflector and experimental positions. The results show that this initial core loading pattern does not yet meet the in-core thermal neutron flux target of $10^{14}$ n cm$^{-2}$ s$^{-1}$ identified in the technical-requirements phase within the intended 5–10 MW power range, indicating that alternative core loading patterns will need to be studied in the forthcoming conceptual design phase.

## 1 INTRODUCTION

Nuclear research reactors (RR) represent an essential part of the nuclear infrastructure: they advance nuclear science and technology, provide education and training for nuclear professionals, ensure the production of medical isotopes, and enable the testing of future energy technologies such as fusion, small modular reactors (SMRs) and Generation IV reactors, in addition to numerous other applications [1].

The number of operable research reactors has been decreasing globally, with Europe at the forefront of this negative trend due to the lack of new builds and the ageing of the existing fleet. Only three new research reactors are currently under construction in the European Union — Pallas, MYRRHA and JHR — and while each represents a state-of-the-art facility in its own niche application, none provides the versatility and accessibility needed to maintain or advance European nuclear capabilities at large. This gap was highlighted by the Towards Optimized Use of Research Reactors in Europe (TOURR) project, which concluded that at least two additional research reactors should be built in Europe, beyond those already under construction [2].

The VERONICA (Versatile European Reactor for Neutron Irradiation and Nuclear Research) project, a collaboration between the Jožef Stefan Institute (JSI) and CEA, addresses this need by proposing a new dual-core research reactor facility in Slovenia. The facility comprises a Multi-Purpose Research Reactor (MPRR), mainly focused on instrumentation development, specialized industrial and medical applications, radiochemistry, material testing and radiation effects, neutron beam applications and multiphysics research, and a Zero-Power Reactor (ZPR), mainly focused on education and training, reactor design, neutron code validation and benchmark experiments. Beyond addressing the TOURR conclusions, the project is aligned with several EU strategic priorities — including the Green Deal, the Draghi report on European competitiveness, REPowerEU and the Nuclear Illustrative Programme — all of which recognize the role of research infrastructure in supporting the long-term operation of existing reactors and the development of new nuclear power plants and SMRs.

In a companion paper presented at PHYSOR 2026 [3], the technical requirements of both reactors were formalized by mapping more than 35 identified MPRR utilizations and 15 ZPR utilizations onto a three-dimensional phase-space defined by neutron flux, neutron energy spectrum and temperature, building on earlier work identifying the relevant stakeholders and utilizations [4]. The main conclusion of that analysis is that the MPRR should achieve an in-core thermal neutron flux on the order of $10^{14}$ n cm$^{-2}$ s$^{-1}$ in an open pool-type, water-cooled configuration offering a high level of versatility, including the ability to modify the geometric configuration of the core and reflector and to operate under different operating modes across a broad range of applications. The ZPR, in turn, should provide the flexibility required to perform a wide variety of benchmark experiments while supporting high-level education and training.

Building on these conclusions, this paper reports on the progress made in the technical design of the VERONICA facility since the technical-requirements phase, and presents an initial computational characterization of the MPRR. Section 2 describes the main design features of the MPRR and the ZPR. Section 3 presents preliminary Monte Carlo neutron transport calculations providing first estimates of the neutron flux levels achievable in the MPRR for an initial core loading pattern, together with an analysis of the neutron energy spectra and spatial flux distribution at representative positions and a comparison against the design targets. Section 4 concludes the paper and outlines the next steps towards the conceptual design phase.

# 2 TECHNICAL DESIGN DESCRIPTION

## 2.1 Multi-Purpose Research Reactor (MPRR)

The MPRR is being designed as an open pool-type reactor, cooled and moderated by light water, with a design target in-core thermal neutron flux on the order of $10^{14}$ n cm$^{-2}$ s$^{-1}$, reaching up to several $10^{14}$ n cm$^{-2}$ s$^{-1}$ in dedicated high-flux positions, consistent with the technical-requirements analysis [3]. The compact, high-power-density core is surrounded by a heavy-water ($D_2O$) reflector tank, a configuration that provides a large, low-perturbation irradiation volume around the core while extending the accessible neutron spectrum from the fast and epithermal range in and near the core down to thermal and even cold-spectrum conditions in the outer reflector regions. This zoning of flux and spectrum across the core–reflector assembly is the central organizing principle of the MPRR design, since it allows a single facility to serve the very broad range of applications identified in the technical-requirements phase, from fuel and material irradiation to neutron scattering, without requiring dedicated reactors for each niche. Table 1 summarizes the main design targets and experimental capabilities of the MPRR discussed in the remainder of this section. Figure 1 presents a schematic view of a possible design of the reactor core, reflector and other experimental equipment.

Table 1: Summary of MPRR design targets and experimental capabilities.

| **Feature** | **Description / target** |
|---|---|
| Reactor type | Open pool-type reactor, light-water cooled and moderated core, $D_2O$ reflector tank |
| In-core thermal neutron flux | On the order of $10^{14}$ n cm$^{-2}$ s$^{-1}$, up to several $10^{14}$ n cm$^{-2}$ s$^{-1}$ in dedicated positions |
| Neutron spectrum range | Fast/epithermal in and near the core to thermal/cold in the $D_2O$ reflector; epithermal tailoring via spectrum-shifting inserts |
| Multiphysics loop | Steady-state and transient operation with controlled coolant flow rate, inlet temperature and pressure |
| Irradiation environments | High-temperature (fuel/material irradiation) and low-temperature ports via externally heated or cooled capsules and loops |
| Other experimental capabilities | Medical isotope production, silicon doping, neutron beam ports for scattering, radiography and PGAA |

**Spectrum-shifting device.** To address applications whose requirements fall in the epithermal range — including several tests-and-calibrations and nuclear-data-measurement utilizations identified in [3] — a spectrum-shifting device — shown as the "programmable reflector" in Figure 1 — is foreseen in the reflector, based on dedicated neutron filters or absorbers that can be inserted into designated reflector channels. Sufficient space is being reserved around these channels so that filter or absorber inserts can be installed and removed without interfering with safe and stable reactor operation, and so that the achievable degree of spectral tailoring can be extended as the design matures.

**Multiphysics experimental loop.** A dedicated experimental loop is foreseen to support coupled neutronics–thermal-hydraulics (N-TH) investigations, in line with the objectives of the OECD/NEA Expert Group on Reactor Systems Multi-Physics (EGMUP) [5]. The loop will allow controlled variation of coolant flow rate, inlet temperature and pressure, and will be operated under both steady-state and transient conditions to generate benchmark-quality N-TH datasets at flux levels and temperatures representative of the applications identified in [3]. Such datasets are intended to complement the macroscopic validation data currently available from the operating LWR fleet with well-controlled, highly-instrumented measurements suitable for validating advanced, physics-based coupled models at the pin- and sub-channel scale.

**High- and low-temperature irradiation ports.** Because the MPRR is a pool-type, water-cooled facility, elevated irradiation temperatures — required in particular for fuel and material irradiation relevant to Generation IV and fusion technologies — cannot be provided by the primary coolant alone and will instead be achieved through externally heated experimental capsules and loops, similarly to the approach adopted at comparable pool-type facilities such as the OSURR reactor [6]. Dedicated low-temperature ports are likewise foreseen, to support irradiation under conditions more representative of near-ambient or cryogenic operating environments. The core and reflector design reserve sufficient space for the insertion of heaters, cooled capsules and specialized irradiation rigs, so that experiments can be carried out under both high-flux and extreme-temperature conditions simultaneously.

**Other experimental capabilities.** In addition to the facilities described above, the MPRR design includes irradiation positions optimized for medical isotope production and for silicon doping, located in high-flux, high-homogeneity regions of the core periphery and reflector, as well as several neutron beam ports extracted through the $D_2O$ reflector tank wall towards external experimental halls, supporting neutron scattering, neutron radiography, prompt gamma activation analysis and positron-source applications identified in the technical-requirements phase [3].

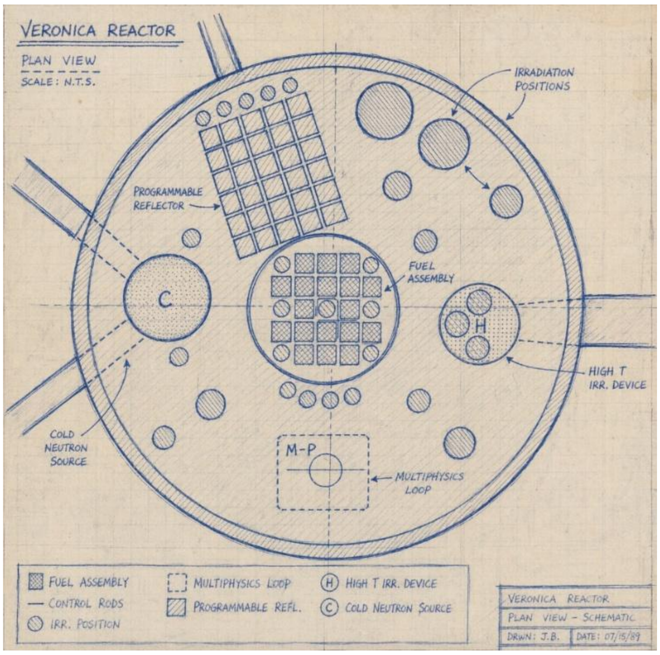


Figure 1: Schematic view of a possible design of MPRR reactor core and the reflector design of the VERONICA facility.

## 2.2 Zero-Power Reactor (ZPR)

The ZPR is a separate, low-power critical assembly dedicated to reactor physics measurements, nuclear data and neutron code validation, benchmark-experiment generation, and high-level education and training, complementing the MPRR without competing with it for irradiation capacity. Because it operates at negligible power, feedback effects are minimal, which makes the ZPR particularly well suited to precise, well-controlled reactor physics measurements and to the safe handling of variable core configurations.

**Flexible core configuration and fuel loading.** The ZPR core is being designed for a high degree of reconfigurability, allowing the lattice pitch, core size and shape, reflector materials and control-element placement to be varied between experimental campaigns. This flexibility will allow a wide variety of benchmark configurations — spanning different moderator-to-fuel ratios and neutron spectra, from thermal to fast — to be assembled in the same facility, broadening the range of code-validation and nuclear-data applications that the ZPR can support. Fuel will be loaded incrementally, following standard approach-to-critical procedures (e.g. 1/M monitoring and Shannon-entropy convergence checks), which enables safe and well-characterized reconfiguration between campaigns.

**Experimental capabilities.** The ZPR is intended to support the measurement of integral and kinetic reactor physics parameters — including reactivity worth, the effective delayed neutron fraction and the prompt neutron generation time — as well as the generation of new benchmark experiments compatible with the ICSBEP/IRPhEP format [7], hands-on training for students and nuclear professionals, and the validation of novel instrumentation and measurement techniques ahead of their deployment in the higher-flux, higher-consequence MPRR environment.

**Zero-power thermal feedback** studies are also considered, where part of the coolant/core could be externally heat-up for the studies of the temperature feedback effects on neutron core parameters for various fuel types.

# 3 PRELIMINARY COMPUTATIONAL CHARACTERIZATION

## 3.1 Computational Model and Methodology

A preliminary three-dimensional Monte Carlo neutron transport model of the MPRR core and $D_2O$ reflector tank has been developed using OpenMC (version 0.14.0) [8], based on the design features described in Section 2.1. Because the VERONICA MPRR is still at an early, pre-conceptual design stage, its technical data and geometric characteristics were derived from similar, already operating or recently commissioned multi-purpose research reactor concepts, namely OPAL [9], RA-10 [10], RMB [11] and JRTR [12]. Standard low-enriched uranium-silicide (U-Si) plate-type fuel elements, of the type used in JRTR and OPAL, were modelled with a cylindrical $D_2O$ reflector tank of 125 cm radius surrounding the core, giving a core loading pattern of 17 fuel elements arranged around 8 in-core irradiation positions. The purpose of the calculations at this stage is not to finalize the design, but to verify that the flux-level and spectral-versatility targets identified in the technical-requirements phase [3] are attainable within the proposed core–reflector concept, and to identify first-order sensitivities that will guide the forthcoming conceptual design phase.

## 3.2 Neutron Flux Levels

Table 2 presents preliminary estimates of the neutron flux level (thermal, epithermal and fast) at representative positions within the MPRR core, reflector and experimental loop, computed with the model described in Section 3.1 at a nominal reactor power of 10 MW. Because VERONICA is being sized within a 5–10 MW power range, corresponding values for the lower end of that range are also given, obtained by linearly scaling the 10 MW result (i.e. taken as one half of the 10 MW value); this is a reasonable first-order approximation at this preliminary stage, since fission power and neutron flux are expected to scale approximately proportionally.

Table 2: Preliminary OpenMC estimates of the neutron flux level at representative MPRR positions, for reactor operation in the 5–10 MW power range.

| **Position** | **Thermal flux (< 0.625 eV) [n cm$^{-2}$ s$^{-1}$]** | **Epithermal flux (< 100 keV) [n cm$^{-2}$ s$^{-1}$]** | **Fast flux [n cm$^{-2}$ s$^{-1}$]** |
|---|---|---|---|
| In-core – central position | (0.5–1) × $10^{13}$ | (1–2) × $10^{13}$ | (1–2) × $10^{13}$ |

| | | | |
|---|---|---|---|
| In-core – periphery position | (1.5–3) × $10^{13}$ | (1–2) × $10^{13}$ | (0.75–1.5) × $10^{13}$ |
| $D_2O$ reflector – near-core position | (2–4) × $10^{13}$ | (0.5–1) × $10^{13}$ | (1.5–3) × $10^{12}$ |
| $D_2O$ reflector – outer / cold position | (2.5–5) × $10^{12}$ | *Negligible* | *Negligible* |
| Multiphysics loop position | (1–2) × $10^{13}$ | *Negligible* | *Negligible* |
| Extracted beam port (ex-core) | (0.5–1) × $10^{13}$ | *Negligible* | *Negligible* |

The highest thermal neutron flux is obtained in the $D_2O$ reflector – near-core position, reaching (2–4) × $10^{13}$ n $cm^{-2}$ $s^{-1}$ over the 5–10 MW power range, closely followed by the in-core – periphery position at (1.5–3) × $10^{13}$ n $cm^{-2}$ $s^{-1}$. The in-core – central position shows a comparatively lower thermal component but the largest epithermal and fast components of all positions investigated, consistent with its hard-spectrum role. The $D_2O$ reflector – outer / cold position, the multiphysics loop position and the extracted beam port all show a strongly thermalized, low-flux spectrum, with epithermal and fast components negligible at these positions, as expected given their distance from the core.

### 3.3 Neutron Energy Spectra and Flux Distribution

To complement the integral flux values in Table 2, the full neutron energy spectrum was computed at the in-core – central, $D_2O$ reflector – near-core, and multiphysics loop positions (Figure 2). The in-core – central position shows a spectrum dominated by the epithermal and fast ranges, while the $D_2O$ reflector – near-core and multiphysics loop positions show progressively softer, more thermalized spectra, consistent with Table 2.

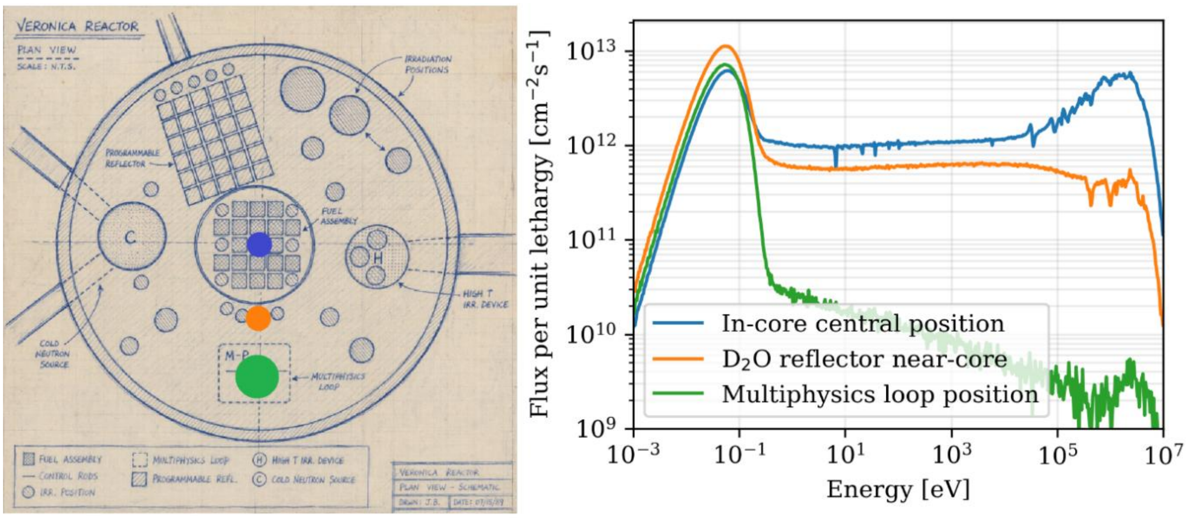


Figure 2: Neutron energy spectra at the in-core – central, $D_2O$ reflector – near-core, and multiphysics loop positions (Table 2). Spectra are normalized at 5 MW of reactor power.

The corresponding spatial distribution of the thermal and fast neutron flux across the core and $D_2O$ reflector (Figure 3) provides a two-dimensional view of the flux gradients underlying the position-by-position values in Table 2, and will help identify the regions that most closely approach the design requirements identified in [3].

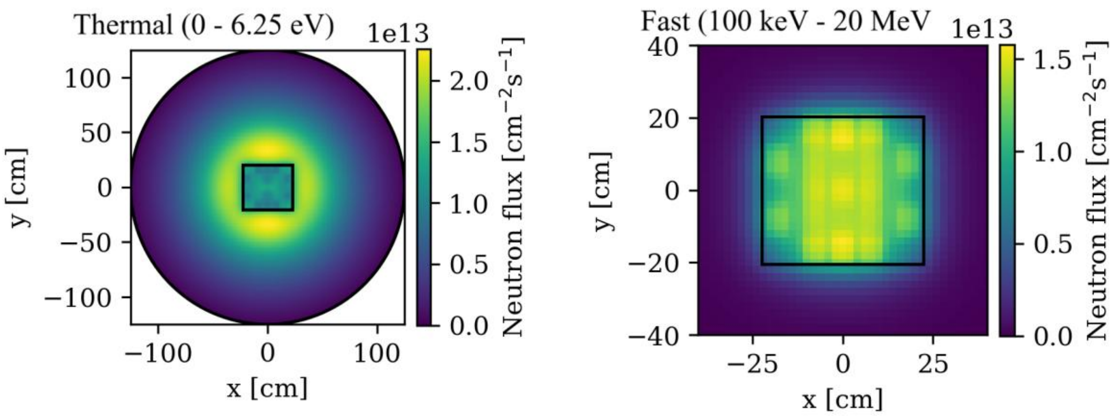


Figure 3: Spatial distribution of the thermal and fast neutron flux across the MPRR core and reflector.

### 3.4 Comparison with Design Targets

Taken together, the preliminary flux results show that the present MPRR core design — 17 fuel elements arranged around 8 irradiation positions (Figure 1) — does not meet the technical design specification identified in the technical-requirements phase [3]. The highest thermal flux obtained, (2–4) × $10^{13}$ n cm$^{-2}$ s$^{-1}$ in the $D_2O$ reflector – near-core position, remains a factor of 2.5 to 5 below the $10^{14}$ n cm$^{-2}$ s$^{-1}$ design target across the 5–10 MW power range, with no position approaching the target even at 10 MW. Achieving $10^{14}$ n cm$^{-2}$ s$^{-1}$ will therefore require either the study of alternative core loading patterns in the forthcoming conceptual design phase — e.g. a higher fuel loading density, a more compact core, or a revised core–reflector geometry — or a re-evaluation of the intended power range. The ZPR will subsequently play a central role in de-risking novel instrumentation and validating the computational models used here, before their deployment in the higher-consequence MPRR environment (Section 2.2).

## 4 CONCLUSIONS

This paper reported on the progress made in the technical design of the VERONICA facility, covering both the Multi-Purpose Research Reactor and the Zero-Power Reactor. The MPRR design combines a compact, high-power-density core with a $D_2O$ reflector tank to provide a broad range of flux levels and neutron spectra within a single facility, complemented by a spectrum-shifting device, a dedicated multiphysics experimental loop, high- and low-temperature irradiation ports, and additional capabilities for isotope production, silicon doping and neutron beam applications. The ZPR design emphasizes a flexible, reconfigurable core and fuel-loading approach, providing the versatility needed to support reactor physics measurements, code and nuclear-data validation, benchmark-experiment generation and high-level education and training.

Preliminary Monte Carlo neutron transport calculations were presented for a first MPRR core loading pattern of 17 fuel elements and 8 irradiation positions, providing first estimates of the thermal, epithermal and fast neutron flux in the core, reflector and experimental positions. A key conclusion is that this core loading pattern does not meet the in-core thermal neutron flux target of $10^{14}$ n cm$^{-2}$ s$^{-1}$ within the intended 5–10 MW power range: the highest flux obtained, in the $D_2O$ reflector, remains a factor of 2.5 to 5 below target. Achieving this target at 5 MW will require either the study of alternative core loading patterns in the conceptual design phase, informed by the spectral and spatial flux analysis of Section 3.3, or a re-evaluation of the intended power range.

By reporting on the progress in the technical design of the VERONICA facility and on the preliminary computational characterization of the MPRR, this paper aims to contribute to the ongoing European nuclear dialogue and to invite collaboration and feedback from the wider nuclear science and technology community as the project advances towards its conceptual design phase with the emphasis on the future study of MPRR final power and flux levels and ZPR features.

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