Overview of the European Supercritical-Water-Cooled Small Modular Reactor Concept

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This paper presents the European Supercritical-Water-Cooled Small Modular Reactor (SCW-SMR) concept developed within the ECC-SMART project, a joint European-Canadian-Chinese initiative. The 290 MWth reactor operates at 25 MPa with a core outlet temperature of 500 °C, achieving 44 % net thermal efficiency. The innovative horizontal fuel-assembly arrangement with seven heat-up stages and intermediate mixing plenums enables fully passive decay heat removal through natural circulation, even without operator intervention or external power for >72 hours. The compact pressure vessel (4.17 m inner diameter) contains 400 fuel assemblies in a 20×20 square lattice. System-level safety analyses demonstrate that all design-basis accidents are mitigated exclusively by passive systems, eliminating the need for high-pressure injection. The large subcooled water inventory and unique in-vessel natural circulation patterns limit peak cladding temperatures to <625 °C in normal operation and <780 °C during accidents. By integrating the high efficiency of supercritical-water cooling with inherently safe, fully passive features, the ECC-SMART SCW-SMR offers a promising Generation IV solution tailored to European energy and safety requirements.

Keywords: SCW-SMR, supercritical water reactor, passive safety, horizontal fuel assemblies, natural circulation, Generation IV, ECC-SMART

1 Introduction

Supercritical water-cooled reactors (SCWRs) are one of the six Generation IV concepts selected by the Generation IV International Forum (GIF) for their potential to deliver enhanced sustainability, economic competitiveness, safety, and proliferation resistance [1]. By operating above the critical point of water (374 °C, 22.1 MPa), SCWRs employ a single-phase supercritical fluid as coolant, enabling net thermal efficiencies above 44 %, substantially higher than the 33–35 % typical of current light-water reactors (LWRs). This is achieved through a direct once-through cycle with high-enthalpy steam supplied to the turbine, reducing both capital and fuel-cycle costs [2]. The growing demand for flexible, cost-competitive nuclear solutions has driven interest in small modular reactor (SMR) variants of the SCWR. According to the European SMR Industrial Alliance [3], SMR deployment in Europe could reach 15 GW by 2050 under baseline conditions, 50 GW with strong policy support, or up to 100 GW in an ambitious Net Zero scenario. With a thermal output of 290 MWth (128 MWe net), the European SCW-SMR is specifically tailored to regional needs, including replacement of retiring coal plants, district heating and industrial process steam supply, and grid-balancing support amid rising renewable penetration.

The ECC-SMART project, a joint European-Canadian-Chinese initiative, aims to develop a passively safe, economically viable SCW-SMR. Building on the European High-Performance Light Water Reactor (HPLWR) experience Schulenberg and Starflinger [4], the project integrates insights from Canadian pressure-tube SCWR concepts Yetisir et al. [5]; Nava Dominguez et al. [6] and Chinese mixed-spectrum and two-pass core designs Wu et al. [7]. The European SCW-SMR concept was first presented in Schulenberg and Otic [8, 9, 10].

This paper describes the current ECC-SMART reference design for a European SCW-SMR [11]. Section 2 details the reactor core, fuel assembly, and passive safety systems. Section 3 presents thermal-hydraulic analysis. Section 4 analyzes design-basis accidents, emphasizing fully passive decay heat removal and the unique natural circulation behavior enabled by the horizontal core layout. Section 5 compares the European design with Canadian and Chinese SCW-SMR variants and other SMR concepts. Section 6 summarizes key achievements and identifies priorities for future development.

2 Design Concept

The European SCW-SMR employs an innovative reactor pressure vessel (RPV) design that prioritizes passive safety features and operational simplicity while maintaining economic competitiveness. The primary innovation of the European SCW-SMR (EU-SCW-SMR) consists of its horizontal fuel assembly orientation with seven sequential heat-up stages and intermediate mixing zones. This configuration specifically addresses fundamental challenges identified in earlier SCWR concepts Oka et al. [12]; Schulenberg and Starflinger [13]. The elimination of siphon effects that prevented natural circulation in two- and three-pass vertical designs represents a breakthrough in passive safety capability of the novel EU-SCW-SMR concept. The design reduces peak cladding temperatures through enhanced mixing between heat-up stages while promoting passive safety through buoyancy-driven circulation. Additionally, the horizontal configuration simplifies control rod mechanisms through transverse insertion, eliminating the complexity and safety concerns associated with top-entry control rod drives. The design philosophy prioritizes passive and inherent safety features consistent with Generation IV objectives, particularly the goal of eliminating the need for offsite emergency response. This approach aligns with current regulatory trends that favor designs capable of demonstrating safety through natural circulation rather than active engineered systems. The reactor's principal design parameters are presented in Table 1.

Core Configuration and Flow Path

The reactor core features a distinctive horizontal fuel assembly arrangement within a square lattice configuration, as illustrated in Figure 1. This horizontal orientation represents a fundamental departure from conventional vertical designs and enables enhanced natural circulation capabilities during accident scenarios. The core comprises 400 fuel assemblies arranged in a 20×20 array, with each assembly containing 32 fuel rods in a wire-wrapped configuration for optimal heat transfer performance.

The coolant flow path through the seven-stage configuration is carefully optimized to balance thermal performance with hydraulic requirements. Feedwater enters the reactor vessel at 280°C through two opposing inlet nozzles, flows downward through the downcomer annulus, and collects in the lower plenum.

Table 1: Main design parameters of the European SCW-SMR

Parameter	Value
Thermal power	290 MWth
Electrical power (net)	128 MWe
Thermal efficiency	44.1%
Operating pressure	25 MPa
Core inlet temperature	280°C
Core outlet temperature	500°C
Core flow rate	145 kg/s
RPV inner diameter	4.17 m
Active core height	1.94 m
Number of fuel assemblies	400
Fuel assembly array	20×20
Number of heat-up stages	7

From there, the coolant enters the horizontal fuel assemblies and progresses through seven sequential heat-up stages guided through the steel staircase, see Figures 1 and 2. The first three stages contain 40 assemblies each (arranged in two rows), stages four and five contain 60 assemblies each (three rows), and the final two stages contain 80 assemblies each (four rows). This progressive increase in number of assemblies compensates for the decreasing coolant density as temperature rises, maintaining uniform mass flow distribution across all stages. This arrangement maintains uniform pressure drop characteristics across all stages while promoting thorough mixing between stages to minimize hot spots and temperature peaking factors. This arrangement with increasing assembly count and dedicated mixing plenums is a distinguishing feature of the EU-SCW-SMR horizontal-core design, contributing to both thermal-hydraulic uniformity and enhanced passive safety performance.

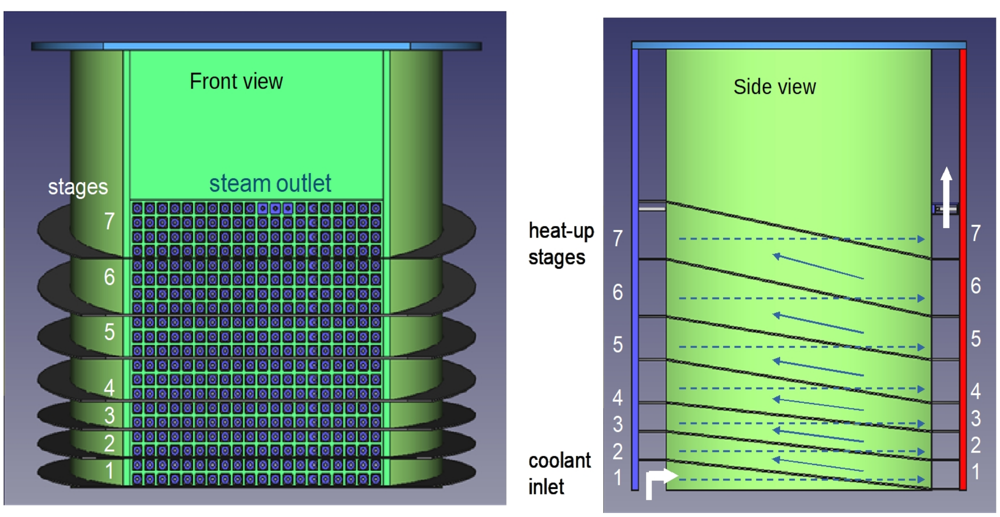

Figure 1: Core design with horizontal fuel assemblies and 7 heat up stages with intermediate mixing

Figure 2 illustrates the flow path through the reactor pressure vessel. Feedwater enters at 280°C through two opposite nozzles and flows downward through the annular downcomer. After passing through the lower plenum, approximately 8.3% of the flow enters the annular radial reflector region surrounding the core barrel, while the majority flows through the core assembly channels. The moderator flow, representing about 10% of the total flow, passes through the central water boxes within each fuel assembly to maintain neutron moderation.

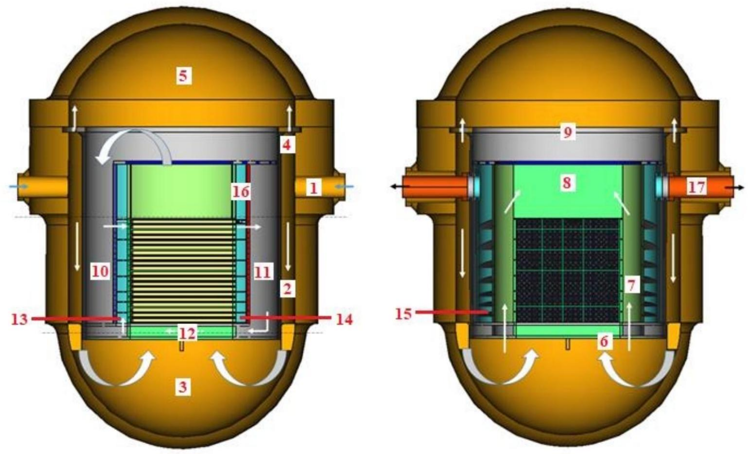

Figure 2: Vertical cross-section of the SCW-SMR RPV showing the flow path

Between stages, the coolant flows through spiral channels formed around the core perimeter, ensuring thorough mixing and preventing hot spot formation. Finally, the superheated steam at approximately 500°C is collected in the annular steam dome above the core and exits through two hot leg nozzles. Further details on the EU-SCW-SMR core design together with the detailed description of the flow path can be found in Schulenberg and Otic [8, 9, 10]; Otic et al. [14]. The seven-pass flow scheme represents a key innovation enabling both improved thermal performance and passive safety capabilities. Table 2 details the distribution of fuel assemblies across heat-up stages.

Table 2: Distribution of fuel assemblies in heat-up stages

Heat-up Stage	FA Rows	FAs per Row	Total FAs
1	2	20	40
2	2	20	40
3	2	20	40
4	3	20	60
5	3	20	60
6	4	20	80
7	4	20	80
Total	**20**	-	**400**

The increasing number of parallel assemblies in higher stages compensates for decreasing coolant density, maintaining relatively uniform pressure drop across all stages, a significant improvement over earlier two- and three-pass designs that suffered from flow instabilities and hot spots, see Schulenberg and Starflinger [13]; Otic et al. [14]; Andreani et al. [15].

Fuel Assembly Design

The fuel assembly design addresses the dual challenges of high-temperature operation and neutron economy through a sophisticated multi-layer construction. Each assembly measures 195 mm square and contains 32 fuel rods arranged in a regular pattern. The fuel rods utilize UO_2 pellets with enrichment varying from 5.5% to 8.0% U-235, depending on the assembly location and heat-up stage. The fuel assembly design is basically identical to the previous HPLWR assembly design, see Schulenberg and Starflinger [13]. The cladding material is 310S stainless steel with a wall thickness of 0.5 mm, selected based on extensive corrosion testing within the ECC-SMART materials program. However, subsequent long-term experimental investigations conducted under representative supercritical water conditions indicate that Alloy 800H offers superior performance and can be therefore adopted as the preferred cladding material, see Šípová [16]; Edwards et al. [17]. The assembly box design employs a sandwich construction comprising a 0.4 mm thick stainless steel liner on the inner surface exposed to high-temperature coolant, a structural Zircaloy-4 wall of 0.8 mm thickness providing mechanical strength with low neutron absorption, and a 2 mm thick zirconia (ZrO_2) thermal insulation layer positioned between them. The inner moderator box follows a similar design philosophy, with a stainless steel liner of 0.4 mm thickness on the outside, a Zircaloy structure with 0.8 mm thickness on the inside, and thermal insulation of 2 mm thickness in between, see Schulenberg and Otic [8]; Otic et al. [14].

Control and Shutdown Systems

The reactor employs a comprehensive dual shutdown system approach for defense-in-depth safety.

The primary shutdown system utilizes control rod clusters inserted horizontally from the side of the reactor vessel, capitalizing on the advantages of the horizontal core configuration. This transverse insertion mechanism simplifies the control rod drive design by eliminating the need for complex mechanisms above the reactor vessel and removes concerns about control rod ejection accidents that can occur in vertical systems. The control rods contain boron carbide (B_4C) absorber material with sufficient negative reactivity worth to achieve cold shutdown from any operating condition, even with the most reactive rod stuck in its withdrawn position. The horizontal insertion path ensures that gravity assists in rod insertion during loss of power events, providing an inherent fail-safe mechanism.

The secondary shutdown system consists of an independent liquid poison injection system capable of introducing soluble boron into the moderator circuit. This system provides diverse shutdown capability essential for defense-in-depth and can maintain subcriticality during long-term cooling phases following accidents.

Both shutdown systems are designed to function passively upon loss of power, with control rods falling into the core under gravity and boron injection valves opening on loss of actuation power, ensuring reactor shutdown without operator intervention or external power sources, see Antók et al. [18].

Safety Systems Design

The EU-SCW-SMR safety design follows defense-in-depth principles with particular emphasis on passive and inherent features that align with Generation IV safety objectives. Figure 3 illustrates the minimum set of safety systems required for the design.

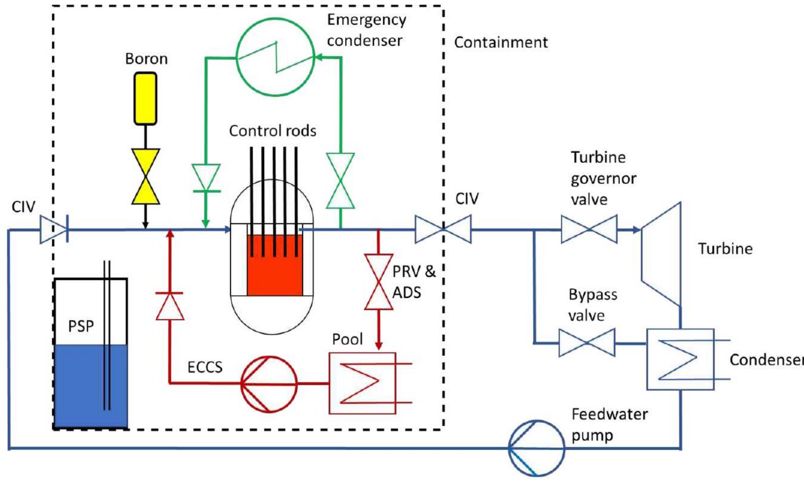

Figure 3: Minimum set of safety systems for the SCW-SMR: Systems for normal operation (blue), active safety systems (red), and passive safety systems (green)

The containment systems provide the third barrier for fission product retention through integrated features that function without external power or operator action. Containment isolation valves (CIVs) automatically close upon detection of accident conditions, isolating the reactor from the environment. The pressure suppression pool (PSP) limits containment pressure increases during steam release events by condensing steam through vent pipes, maintaining containment integrity without active cooling systems.

The passive residual heat removal system represents a critical safety innovation for the EU-SCW-SMR design. The isolation condenser system (ICS) consists of four independent trains, each rated at 3% of nominal power, providing 12% total heat removal capacity with significant redundancy. Natural circulation loops utilize an elevation difference of 15 meters between the core and condensers to provide adequate driving head for circulation without pumps. The system offers flexible heat sink options, including external atmospheric cooling for unlimited heat rejection capacity or internal water pools sized for 72-hour operation without makeup water, allowing adaptation to different siting requirements and regulatory frameworks while maintaining passive operation.

The emergency core cooling systems have been optimized based on the unique characteristics of supercritical water operation. High-pressure injection systems are not required due to the large subcooled water buffer maintained in the reactor vessel during normal operation. This subcooled inventory at 280°C provides significant grace time before core uncovery can occur. The accumulator system consists of four tanks containing borated water at 60°C, providing immediate injection upon depressurization without requiring pumps or valves. Low-pressure injection utilizes gravity-driven flow from elevated pools, ensuring long-term core cooling without active pumps. Further details on the European SCW-SMR concept can be found in Schulenberg and Otic [8, 9, 10], Otic et al. [14]; Antók et al. [18]; ECC-SMART Consortium [19].

Materials Selection

The extensive materials testing campaign within ECC-SMART confirmed that 310S stainless steel provides excellent corrosion resistance in supercritical water environments, with metal penetration below 10 μm after 30,000 hours of operation—far below the 140 μm design requirement. The high chromium content

(24.5-25.5 wt%) ensures formation of a protective Cr_2O_3 layer that remains stable at operating temperatures. Alternative materials including 800H alloy were also qualified, providing further investigations on design improvement, see Šípová [16]; Edwards et al. [17]; Novotný et al. [20]. The selection of Zircaloy-4 for moderator box structures leverages proven LWR experience while maintaining low neutron absorption. The sophisticated multi-layer construction with YSZ thermal insulation ensures structural integrity while minimizing heat transfer between hot coolant and moderator circuits Schulenberg and Otic [8]; Otic et al. [14]. Material considered for the design concept, presented in Table 3, reflect the lessons learned from the HPLWR [13] and ECC-SMART [11] projects.

Table 3: Primary materials selection for EU SCW-SMR

Component	**Material**	**Max. Temperature (°C)**
Fuel cladding	310S stainless steel	625
Assembly box inner liner	310S stainless steel	520
Assembly box structure	Zircaloy-4	320
Moderator box structure	Zircaloy-4	320
Thermal insulation	YSZ (7% Y_2O_3 in ZrO_2)	520
RPV	20 MnMoNi 5 5	280
Core support structures	316L stainless steel	320
Control rod cladding	Inconel 625	500

3 Thermal-Hydraulic Performance

The thermal-hydraulic performance of the European SCW-SMR has been extensively analyzed using multiple computational approaches to ensure robust design validation. Subchannel analyses conducted using both ASSERT-PV SC, Nava-Dominguez et al. [21], and the in-house STAFAS, [14], codes demonstrate good agreement in their predictions, providing confidence in the thermal margins. Maximum cladding temperatures remain below 625°C during normal operation across all seven heat-up stages, with peak values occurring at approximately 60% of the heated length in stage 4, where the combination of power density and coolant temperature creates the most challenging conditions. The hot channel factors determined through these analyses are 1.15 for enthalpy rise, indicating relatively uniform power distribution achieved through careful fuel enrichment zoning and assembly placement optimization. The wire-wrapped spacers effectively promote turbulent mixing within assemblies, reducing local temperature peaks by approximately 30°C compared to grid spacer designs. Computational fluid dynamics simulations reveal the development of secondary flow patterns within the horizontal assemblies that enhance heat transfer coefficients by 10-15% compared to vertical orientations. Further details on the thermal-hydraulic analysis can be found in the publically available report Otic et al. [14].

4 Safety Analysis

The primary objective of the safety analysis was to demonstrate the viability of the proposed passive safety systems and their capability to maintain core integrity during severe accident scenarios. The novel seven-stage horizontal core configuration, while advantageous for natural circulation enhancement, presents unique challenges for safety analysis due to its complex flow paths and reliance on passive mechanisms for accident mitigation. In this section we present a brief summary of the main results provided in Otic et al. [14]; Varju et al. [22]; Varju and Aszódi [23]; Varju et al. [24, 25]; Chaaraoui et al. [26]; Kassem et al. [27].

The comprehensive safety assessment employed multiple computational approaches to provide independent validation. Two system thermal-hydraulic codes, RELAP5 [28] and APROS [29], were utilized to analyze accident progression and validate passive safety system performance. The RELAP5 implementation incorporated modifications to handle supercritical water properties and heat transfer correlations specific to the operating regime. APROS simulations provided complementary insights with enhanced resolution of local thermal-hydraulic phenomena through improved heat transfer correlations developed specifically for supercritical flows.

The SERPENT 2 [30] Monte Carlo code was coupled with APROS to analyze the evolution of the power distribution during transient conditions, thereby revealing key feedback mechanisms. The negative reactivity feedback arising from coolant density variations provides an additional inherent safety margin in the early phase of an accident. In particular, the coolant density coefficient of -2.5 pcm/kg/m³ and the Doppler coefficient of -2.8 pcm/K ensure rapid, negative reactivity insertion during power excursions or loss-of-cooling events. This coupled neutronic–thermal-hydraulic approach demonstrates that the reactor naturally suppresses power excursions through fundamental physical processes rather than relying solely on engineered safety systems.

Key safety innovations emerging from these analyses include the elimination of high-pressure injection requirements through strategic utilization of subcooled water inventory, effective use of the substantial feedwater volume (approximately 100 m³) as a thermal buffer, and successful demonstration of passive decay heat removal for periods exceeding 72 hours without operator intervention.

Long-Term Station Blackout Analysis

The Long-Term Station Blackout (LTSBO) represents one of the most challenging accident scenarios for nuclear reactor design, particularly for concepts relying on passive safety features. Following reactor scram and complete loss of AC power, the reactor protection system successfully initiates shutdown, but all forced circulation pumps coast down, leaving only passive mechanisms available for decay heat removal. The accident progression involves several distinct phases: initial depressurization through the opening of pressure relief valves, establishment of natural circulation flow patterns, activation of passive heat removal systems, and long-term decay heat removal through isolation condensers.

The spatial distribution of temperatures confirms that the seven-stage design effectively manages heat removal across all core regions, with no evidence of flow stagnation or hot spot formation. Peak cladding temperatures reach approximately 680°C during the initial transient phase but stabilize and gradually decrease as natural circulation establishes. The comparison between 25 MPa and 24 MPa operating pressures shows minimal impact on overall safety performance, demonstrating the robustness of the passive safety concept. All seven stages maintain temperatures well below safety limits throughout the transient, with fuel centerline temperatures remaining below 800°C and cladding temperatures staying well under the 850°C design limit. The isolation condenser system maintains stable operation throughout the 72-hour analysis period, with the passive heat removal system tanks reaching equilibrium conditions within 9.5 hours and maintaining adequate water inventory for the entire duration.

Large-Break Loss-of-Coolant Accident Analysis

The Large-Break Loss-of-Coolant Accident (LBLOCA) analysis examined a double-ended guillotine break of the 280°C inlet line. This cold-leg break location presents particular challenges due to the potential for rapid inventory loss and flow stagnation. Both RELAP5 and APROS analyses confirmed that the hot-leg blowdown strategy maintains positive core flow direction throughout the event, preventing flow reversal that could lead to localized overheating.

The large subcooled water inventory prevents immediate core uncovery, providing crucial time for passive system activation. This substantial thermal buffer, combined with the strategic vessel design, ensures that even during rapid depressurization, sufficient coolant remains in contact with fuel assemblies. Peak cladding temperature reaches 780°C at approximately 25 seconds into the transient, remaining below the design limit with adequate margin. The APROS analysis confirmed similar temperature peaks across all seven stages, with the highest temperatures occurring in stages 6 and 7 due to their higher power density. Accumulator injection initiated at 6 MPa provides adequate core cooling without credit for active ECCS pumps, demonstrating the effectiveness of the purely passive mitigation strategy.

Unique Phenomena in Horizontal Configuration

The horizontal core configuration generates complex but robust circulation patterns during accidents that provide multiple, redundant heat removal paths. The primary circulation loop from core to isolation condensers via the upper plenum serves as the dominant heat removal mode, driven by the density difference between hot fluid in the core and cooled fluid returning from the condensers. The APROS-Serpent coupled analysis demonstrated that this circulation mode establishes rapidly, with mass flow rates stabilizing within the first hour and remaining practically constant throughout the extended transient period.

Inter-stage circulation develops between adjacent heat-up stages through mixing channels, equalizing temperatures and preventing isolated hot regions. This phenomenon, unique to the seven-stage horizontal design, was confirmed through both RELAP5 and APROS simulations, showing temperature differences between stages reducing to less than 20°C within minutes of natural circulation establishment. Within individual horizontal assemblies, intra-assembly circulation patterns emerge due to density stratification, creating local convection cells that enhance heat transfer by approximately 15% compared to stagnant conditions.

The radial reflector region contributes significantly to overall circulation stability, with approximately 8.3% of total flow bypassing the core through this path, providing additional cooling to vessel internals and contributing to the mixing in upper and lower plena. These interconnected loops provide redundant heat removal paths and prevent local stagnation zones that could lead to fuel damage, demonstrating the inherent safety advantages of the horizontal configuration over conventional vertical designs where siphon effects and flow reversal remain persistent concerns.

These results confirm that all design-basis accidents are successfully mitigated solely by passive safety systems, eliminating the need for high-pressure injection. This demonstrates the inherently safe, fully passive safety characteristics of the European SCW-SMR design.

5 Comparative Analysis

Table 4 compares safety analysis results across the three reactor concepts developed within the ECC-SMART project, see ECC-SMART documentation [19]. The European SCW-SMR with its horizontal configuration demonstrates improved passive safety performance compared to both the Canadian pressure-tube design and the Chinese vertical RPV concept.

Table 4: Comparison of safety analysis results for ECC-SMART reactor concepts

Parameter	EU SCW-SMR (Horizontal)	Canadian SCW-SMR	Chinese CSR-150
Thermal Power (MWth)	290	300	150
Core Configuration	RPV, Horizontal	Pressure Tube	RPV, Vertical
Flow Passes	7	1	2
PCT in cold-leg LOCA (°C)	780	1003	850
PCT in LTSBO (°C)	680	750	710
NC establishment (s)	200	>600	400
HP injection requirement	Not required	Required	Required

The horizontal configuration shows particularly strong advantages in natural circulation establishment time and elimination of high-pressure injection requirements. Table 5 presents a broader comparison with competing SMR technologies.

Table 5: Comparison of SCW-SMR with competing SMR technologies

Parameter	SCW-SMR	iPWR	BWR-SMR	HTGR	MSR
Power (MWe)	128	50-300	50-300	50-200	100-300
Efficiency (%)	44	33	34	42	45
Outlet temp. (°C)	500	320	285	750	700
Passive safety	Excellent	Good	Good	Excellent	Good
Capital cost (€/kW)	3500	4500	4200	5000	4000

Economic Competitiveness

The European SCW-SMR demonstrates strong economic potential through several key advantages. The high thermal efficiency of 44% reduces fuel consumption by approximately 25% compared to conventional LWRs, translating to lower operational costs over the plant lifetime. The simplified single-phase coolant system eliminates steam generators and associated components, substantially reducing capital costs. Construction economics benefit from extensive factory fabrication of the compact reactor vessel and modular components, enabling parallel construction activities and reducing on-site assembly time to 3-4 years. The overnight capital cost is expected to be competitive with other SMR technologies, with potential for further reduction through series production and design standardization. The capital cost estimates presented in Table 5 are preliminary and should be treated as rough approximations only.

6 Conclusions

The European SCW-SMR concept developed within the ECC-SMART project successfully demonstrates the feasibility of combining supercritical water cooling technology with enhanced passive safety features in a small modular configuration. The innovative horizontal seven-stage core design addresses fundamental challenges that have historically limited SCWR deployment while achieving thermal efficiencies approaching 44%.

Key technical achievements include the successful demonstration of passive decay heat removal through natural circulation for extended periods exceeding 72 hours, elimination of high-pressure injection requirements through strategic utilization of subcooled water inventory, and maintenance of peak cladding temperatures within acceptable limits throughout all analyzed scenarios. These results, validated through independent analyses using multiple system codes, confirm the robustness of the passive safety concept.

The comparative assessment reveals superior performance relative to other ECC-SMART concepts, particularly in natural circulation establishment time and grace period for operator intervention. Economic analysis indicates competitive capital costs and operational advantages that position the SCW-SMR favorably for European deployment scenarios.

Future priorities include experimental validation of horizontal assembly thermal-hydraulics in dedicated test facilities, qualification of materials under representative SCW conditions, and refinement of the licensing framework through continued regulatory dialogue. The European SCW-SMR represents a promising pathway toward achieving Generation IV reactor objectives while meeting near-term deployment requirements for flexible, economically viable nuclear energy systems.

Acknowledgments

This paper is based on an invited presentation given at the POWER PLANTS 2025 Conference, Zlatibor Serbia, in November 2025.

This work was supported by the European Commission under the ECC-SMART project (Grant Agreement No. 945234). The author gratefully acknowledge the invaluable contributions from all consortium partners: Budapest University of Technology and Economics, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Research Centre Řež, European Nuclear Education Network, IPP CENTER, Joint Research Centre, Jožef Stefan Institute, Karlsruhe Institute of Technology, Kungliga Tekniska Hoegskolan, Regia Autonome Tehnologii Pentru Energia Nucleara, Slovenska Technicka Univerzita v Bratislave, University of Nottingham, University of Sheffield, University of Pisa, Vysoka Skola Chemicko-Technologicka v Praze, Valtion teknillinen tutkimuskeskus, (Europe); Canadian Nuclear Laboratories, Carlton University (Canada); Nuclear Power Institute of China, Shanghai Jiaotong University, Xi'an Jiaotong University (China). The author thank the International Atomic Energy Agency (IAEA) and Generation IV International Forum (GIF) for providing forums for technical exchange and peer review.

Nomenclature

Abbreviations

ADS	Automatic Depressurization System
APROS	System code
ASSERT-PV SC	Subchannel code
CIV	Containment Isolation Valve
CSR	Chinese Small Reactor
ECC-SMART	Joint European-Canadian-Chinese development of Small Modular Reactor Technology
EU-SCW-SMR	European Supercritical-Water-cooled Small Modular Reactor
ECCS	Emergency Core Cooling System
GIF	Generation IV International Forum
HPLWR	High Performance Light Water Reactor
ICS	Isolation Condenser System
iPWR	Integral Pressurized Water Reactor
LBLOCA	Large-Break Loss-of-Coolant Accident
LOCA	Loss-of-Coolant Accident
LTSBO	Long-Term Station Blackout
LWR	Light Water Reactor
PCT	Peak Cladding Temperature
PSP	Pressure Suppression Pool
RELAP5	System code
RPV	Reactor Pressure Vessel
SCWR	Supercritical Water-cooled Reactor
SCW-SMR	Supercritical-Water-cooled Small Modular Reactor
STAFAS	Inhause KIT Subchannel code
YSZ	Yttria-Stabilized Zirconia

Symbols

MWth	Megawatt thermal
MWe	Megawatt electric
MPa	Megapascal
GWd/tHM	Gigawatt-days per ton of heavy metal
pcm	Per cent mille
wt%	Weight percent

Chemicals

B_4C	Boron carbide
Cr_2O_3	Chromium oxide
UO_2	Uranium dioxide
Y_2O_3	Yttrium oxide
ZrH	Zirconium hydride
ZrO_2	Zirconia (Zirconium dioxide)

References

[1] GIF. Technology roadmap update for generation IV nuclear energy systems. Technical report, OECD Nuclear Energy Agency, Paris, 2014.

[2] I. L. Pioro, editor. *Handbook of Generation IV Nuclear Reactors*. Elsevier Ltd., 1 edition, 2016.

[3] European SMR pre-Partnership. Market potential of SMRs in europe. Technical report, European Commission, Brussels, 2023. URL `https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-industrial-alliance-small-modular-reactors_en`.

[4] T. Schulenberg and J. Starflinger. *High Performance Light Water Reactor—Design and Analysis*. KIT Scientific Publishing, Karlsruhe, Germany, 2012. ISBN 978-3-86644-817-9.

[5] M. Yetisir et al. Development and integration of canadian SCWR concept with counter-flow fuel assembly. *Journal of Nuclear Engineering and Radiation Science*, 1(1):011006, 2013.

[6] A. Nava Dominguez, X. Huang, M. Gaudet, K. Khumsa-Ang, A. D. Mendoza España, J. Chow, D. Roubtsov, and H. Namburi. Progress on a preconceptual supercritical water-cooled small modular reactor. *ASME Journal of Nuclear Engineering and Radiation Science*, 11(3):031301, 2025. doi: 10.1115/1.4068326.

[7] Y. Wu et al. Preliminary safety analysis of the chinese CSR-150 concept. *Nuclear Engineering and Design*, 2025. forthcoming.

[8] T. Schulenberg and I. Otic. Suggestion for design of a small modular SCWR. In *Proc. 10th International Symposium on SCWRs (ISSCWR-10)*, number Paper ISSCWR10-019, Prague, March 15–19 2021.

[9] T. Schulenberg and I. Otic. Conceptual design of structures around the reactor core. Technical Report Project document, ECC-SMART, 2021.

[10] T. Schulenberg and I. Otic. Concept of a small modular SCWR with horizontal fuel assemblies. *ASME Journal of Nuclear Engineering and Radiation Science*, 8(3):031104, 2022.

[11] ECC-SMART project webpage. `https://cordis.europa.eu/project/id/945234`, 2020. last visited: 20.10.2025.

[12] Y. Oka, S. Koshizuka, Y. Ishiwatari, and A. Yamaji. *Super Light Water Reactors and Super Fast Reactors: Supercritical-Pressure Light Water Cooled Reactors*. Springer, Boston, 2010.

[13] Thomas Schulenberg and Jörg Starflinger, editors. *High Performance Light Water Reactor : Design and Analyses*. KIT Scientific Publishing, Jun 2012. doi: 10.5445/KSP/1000025989.

[14] I. Otic, W. Schulenberg, T. Ambrosini, , A. Pucciarelli, O. Chaaraoui, T. Varju, A. Kiss, B. Babcsány, Cs. Antók, P. Mészáros, Z. Bertesina, Sz. Czifrus, V. Filonov, D. Fedorov, Y. Filonova, Y. Dubyk,

A. Nava-Dominguez, and X. Zhao. Report on the preconceptual studies on the core layout and passive safety concept of the SCW-SMR (D3.3), ECC-SMART project report. Project Report Deliverable D3.3, ECC-SMART Project, 2024.

[15] M. Andreani, D. Bittermann, Ph. Marsault, O. Antoni, A. Keresztúri, M. Schlagenhaufer, A. Manera, M. Seppälä, and J. Kurki. Evaluation of a preliminary safety concept for the HPLWR. *Progress in Nuclear Energy*, 55:68–77, 2009. doi: 10.1016/j.pnucene.2011.11.004. URL `https://doi.org/10.1016/j.pnucene.2011.11.004`.

[16] M et al. Šípová. Report summarising the results of corrosion tests with pre-irradiated material. Technical Report Deliverable D2.4, ECC-SMART, 2024.

[17] M. Edwards, J Macák, and R Novotný. Report summarising the results on the scw smr chemistry and changes in the chemical properties of SCW in the behaviour of candidate materials. Technical Report Deliverable D2.5, ECC-SMART, 2024.

[18] Cs. Antók, Sz. Czifrus, and V. Giusti. Neutronic calculations for preliminary core design of SCW-SMR. *Annals of Nuclear Energy*, 209:110805, 2024. doi: 10.1016/j.anucene.2024.110805. URL `https://doi.org/10.1016/j.anucene.2024.110805`.

[19] ECC-SMART Consortium. Deliverables D2.2, D3.3, D3.6, D4.3, D5.3. European Commission CORDIS Database, `https://cordis.europa.eu/project/id/945234/reporting`, 2024.

[20] R Novotný, M Šípová, and M. Novák. Report summarising the results of the out-of-pile corrosion tests. Technical Report Deliverable D2.3, ECC-SMART, 2025.

[21] Armando Nava-Dominguez, Xianmin Huang, and Songyu Liu. Studies of the thermalhydraulics sub-channel code assert-pv 3.2-sc for supercritical applications. *Journal of Nuclear Engineering and Radiation Science*, 11(2):021402, 11 2024. ISSN 2332-8983. doi: 10.1115/1.4066523. URL `https://doi.org/10.1115/1.4066523`.

[22] T. Varju, A. Kiss, Cs. Antók, B. Babcsány, I. Boros, P. Mészáros, Z. Bertesina, and Sz. Czifrus. Current results of BME NTI in the ECC-SMART project: Different analysis on the SCW-SMR. In *Proc. ICONE31 Conference*, Prague, Czech Republic, August 4–8 2024. doi: 10.1115/ICONE31-135760. URL `https://doi.org/10.1115/ICONE31-135760`.

[23] T. Varju and A. Aszódi. Parameter analysis of the cold-leg LBLOCA initiating event of the SCW-SMR reactor concept. *Nuclear Engineering and Design*, 2025. under review.

[24] T. Varju, B. Babcsány, P. Mészáros, Cs. Antók, and Sz. Czifrus. Coupled reactor physics and thermal hydraulics analysis of an SCW-SMR reactor concept – part I: Model development and demonstration. *Annals of Nuclear Energy*, page 111222, 2025. doi: 10.1016/j.anucene.2025.111222. URL `https://doi.org/10.1016/j.anucene.2025.111222`.

[25] T. Varju, Cs. Antók, P. Mészáros, and B. Babcsány. Coupled reactor physics and thermal hydraulics analysis of an SCW-SMR reactor concept – part II: Improvement of the concept and sensitivity analyses. *Annals of Nuclear Energy*, 217:111221, 2025. doi: 10.1016/j.anucene.2025.111221.

[26] O. Chaaraoui, A. Pucciarelli, W. Ambrosini, I. Otic, T. Schulenberg, C. Allison, and Z. Fu. Customising a system code for the analysis of the thermal-hydraulic behavior of a supercritical pressure light water small modular reactor. In *Proc. 31st Int. Conf. on Nuclear Engineering (ICONE31)*, Prague, Czech Republic, August 4–8 2024.

[27] S. Kassem, A Pucciarelli, and W. Ambrossini. Analysis of existing correlations for heat transfer to supercritical pressure fluids in support to the ecc-smart project. Technical Report Technical Report, ECC-SMART, 2021.

[28] RELAP5 webpage. `https://inl.gov/relap53d/`. last visited: 17.11.2025.

[29] APROS webpage. `https://www.apros.fi/`. last visited: 16.11.2025.

[30] J. Leppänen et al. The Serpent monte carlo code: Status, development and applications in 2013. *Annals of Nuclear Energy*, 82:142–150, 2015. doi: 10.1016/j.anucene.2014.08.024. URL `https://doi.org/10.1016/j.anucene.2014.08.024`.

Submitted: 25.11.2025.
Revised: 20.12.2025.
Accepted: 26.12.2025.