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Development Of Small Modular Reactor Cooled by Supercritical Water Within The ECC-SMART Project.

Monika Sipova
Organization: Centrum Výzkumu Řež (CVŘ)
Address: Hlavní 130, Řež, 250 68 Husinec, Czech Republic
E-Mail: monika.sipova@cvrez.cz
Alberto Sáez-Maderuelo
Organization: Center for Energy, Environmental and Technological Research (CIEMAT)
Centro de la Monclo Complutense 40, 28040 Madrid, Spain
E-mail: alberto.saez@ciemat.es
Ivan Otic
Organization: Karlsruhe Institute of Technology (KIT)
Address: Kaiserstrasse 12, 76131 Karlsruhe, Germany
E-mail: ivan.otic@kit.edu
Szabolcs Czifrus
Organization: Budapest University of Technology and Economics (BME)
Address: 1111 Budapest, Műegyetem rkp. 3., Hungary
E-Mail: czifrus@reak.bme.hu
Leon Cizelj
Organization: Institut Jožef Stefan (JSI)
Address: Jamova cesta 39, 1000 Ljubljana, Slovenia
E-mail: leon.cizelj@ijs.si

ABSTRACT

The ECC-SMART: Joint European-Canadian-Chinese development of small modular reactor technology is Euratom Horizon 2020 project. The project started in September 2020 and will end in February 2025. The ECC-SMART project reunites specialists from 17 countries and three continents. It profits from the cooperation and knowledge obtained within previous international projects.

The ECC-SMART aims to make real progress towards the design of an advanced small modular reactor cooled by supercritical water (SCW-SMR). The use of passive safety systems is one of the most important principles on which this type of reactor will be designed. This contribution describes the implementation of the project and how the stated objectives have been fulfilled within four technical work packages (Material testing, Thermal-hydraulics and safety, Neutronics and reactor physics, and Guideline synthesis and pre-licensing studies). The most interesting results obtained so far are presented as well. However, the successful project completion is indicated by submitting 30 deliverables and 20 milestones. In addition, a high number of students were successfully involved and supported the project´s results which were also reflected in published numerous peer-reviewed open-access scientific papers. Overall ECC-SMART project can be considered as an important contributor to the new type of advanced SMRs since SCW-SMR could be utilized in other industrial processes and technologies.

1 INTRODUCTION

Water is widely used worldwide for energy production, whether in fossil-fired power plants (FFPP) or nuclear ones. In the case of FFPP, water is partially used in its supercritical (SC) state, in contrast to NPP operating in subcritical conditions of water. The supercritical conditions in other worlds higher working parameters as pressure and temperature result in the increase of thermal efficiency. Such change generally improves fuel utilization per unit amount of power. Current supercritical FFPP possess overall plant thermal efficiencies of up to 50% whereas water-cooled NPP achieve efficiencies around 35% [1]. The increased efficiency is one of the motivation project of ECC-SMART, which means Joint European-Canadian-Chinese development of Small ModulAr Reactor Technology.

The ECC-SMART project [2] is supported by Horizon 2020 EURATOM call NFRP-2019-2020-05. This project was supported by almost 4 millions EUR divided among the 16 partners (Figure 1) based on their planned activities. This sum was supplemented with additional funding coming from 4 non-European partners (Figure 1). The project was launched in September 2020 and due to restrictions related to the COVID-19 pandemic, the duration was eventually prolonged up to 54 months with the end of February 28, 2025.

Figure 1: Partners of the ECC-SMART projects.

The project ECC-SMART follows the success of the previous international project with a focus on supercritical water reactors, namely HPLWR, HPLWR-Phase 2, FQT-SCW described in [3]. In contrast to the mentioned projects, the ECC-SMART is dedicated to small modular reactors (SMRs) which can be generally defined as reactors with output power up to 300 MWe [4]. According to the International Atomic Energy Agency (IAEA), there are about 70 SMR concepts, which are different in coolant and fuels, and differ in technology readiness, licensing readiness, and modularity. In addition, about 50% of those developed concepts fall into the category of Generation IV as well as small modular reactors cooled by supercritical water investigated by the ECC-SMART project.

The uniqueness of ECC-SMART is that the main goal is to collect all experience from design studies in EU, Canada and China to create a joint design requirements document focused on future SCW-SMR technology. As part of the ECC-SMART project, a pre-licensing study is being developed, along with guidelines for safety demonstration in the further stages of SCW-SMR concept development, including the methodologies and tools to be used. All project results are summarized in 30 deliverables (partly public available) and 20 milestones submitted on the European Commission portal. This contribution describes the progress and some of the most interesting results achieved within the 48 months of the ECC-SMART project.

2 RESULTS AND DISCUSSION

The project consortium consists of 20 partners (see Figure 1) worldwide as there is 1 from Canada, 3 from China, 15 from the EU, and 1 from Ukraine. Next to 11 research centres, 9 universities are actively involved in the project. All mentioned partners contribute to different work packages (WPs) according to their abilities, facilities and manpower. The ECC-SMART is divided into 6 work packages (four technical and two administrative) as it is illustrated in Figure 2.

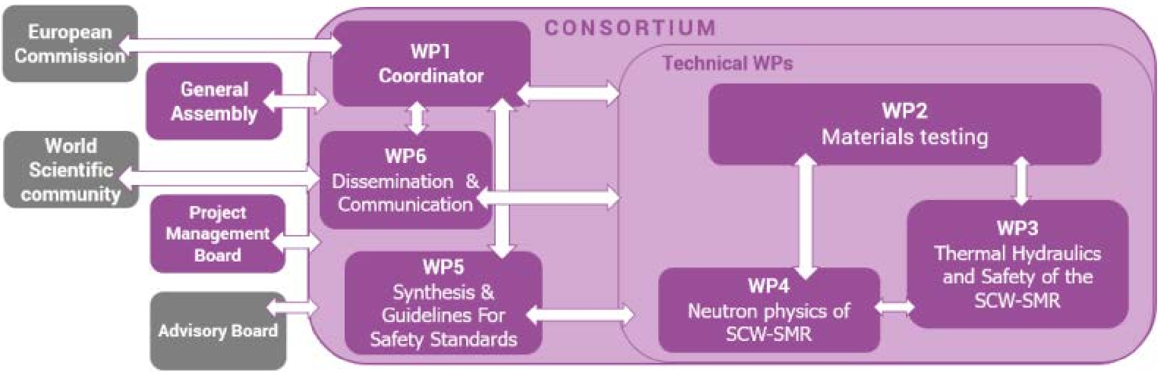


Figure 2: Infographics showing the project structure.

The four technical WPs are complemented by two supportive administrative work packages. WP1 focuses on project coordination, while WP6 manages dissemination and communication, promoting the project through various channels. WP6 also maintains an internal communication SharePoint and supports workshops and educational activities.

Under WP2 dealing with materials for the future SCW-SMR around 800 specimens (Figure 3) were tested in simulated working conditions by different tests. The test matrix reflects the knowledge gaps, with special attention paid to the fuel cladding of SCW-SMR. Therefore, most of the specimens were cut from tubes of 10 mm in dimension. Stainless steel 310S and alloy 800H have been considered the candidate materials for SCWR and the matrix was completed by the experimental AFA (alumina-forming austenitic) material based on 310S. In Figure 3, there are sketches of specimens tested in WP2.

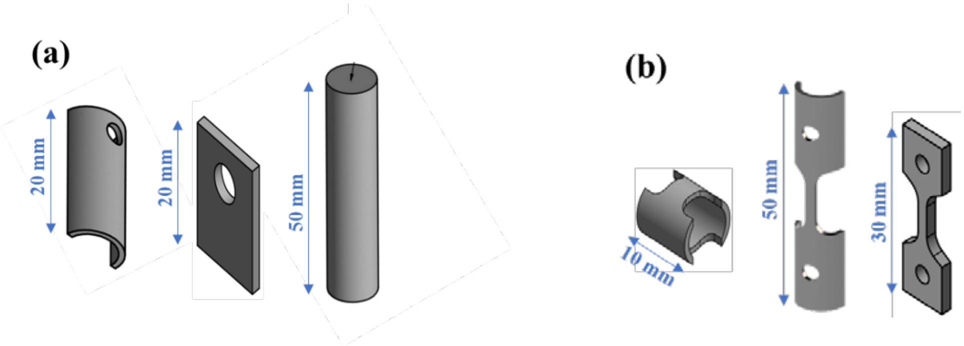


Figure 3: Spectrum of specimens used in WP2; (a) specimens for studying the corrosion behaviour and (b)specimens for testing mechanical properties and the susceptibility to cracking initiation under SCW conditions.

The long-term corrosion tests up to 7000 h were successfully performed in supercritical water (SCW) at pressure 25 MPa and two selected temperatures, specifically 380 °C (pseudocritical point) and 500 °C corresponding outlet temperature of SCW-SMR. Concerning AFA, the effect of pre-oxidation on improved corrosion resistance was verified by exposures in SCW at both temperatures and water pressure 25 MPa up to 3000 h. The exposed specimens were examined using scanning electron microscopy, XRD and surface roughness measurements. In addition, the effect of pressure on the corrosion behaviour was investigated as some of the exposures in SCW were performed at a lower water pressure of 23 MPa.

EAC (environmentally assisted cracking) was assessed by conducting slow strain rate tests (SSRT) in SCW at both temperatures and pressure of 25 MPa loading specimens at a strain rate of 10^{-7} s^{-1}. Moreover, these tests were complemented by the SSRT at a higher strain rate of 10^{-6} s^{-1} to observe the effect of the strain rate on SCC (stress corrosion cracking) initiation. The fractography analyses were completed as well. Currently, the SSRT tests for AFA have been ongoing.

The long-term exposure tests proofed very good corrosion resistance of both candidate materials. In Figure 4 you can see an example of oxidation layer on 310S (left) and 800H (right) after 10 000 h in 500°C/25MPa.

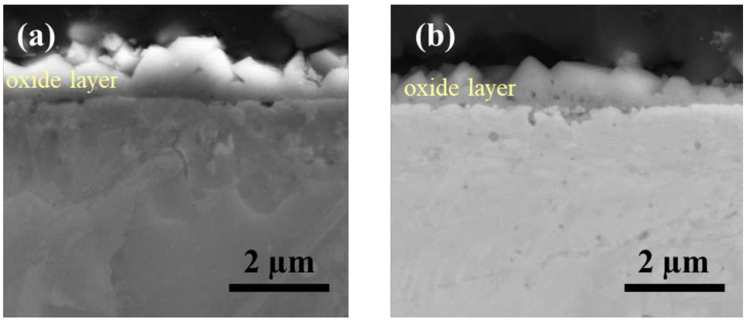


Figure 4: The oxide layer on 310S (a) and 800H (b) after exposure in SCW/500 °C/25 MPa for 10 000 h.

Since many exposure tests have been performed, the data were used to optimize the model predicting the penetration depth [5], which is one of the requirements for structural material for NPPs. It was found for both alloys, it would result in < 20 µm wall penetration in 30 000 h [6].

Exposure tests were completed by electrochemical measurements, which were successfully performed despite the lower conductivity of SCW [7]. The pilot experiment dealing with exposure of pre-irradiated specimens in SCW was finally also performed in hot cells of CVR. Thus, very unique results were achieved.

WP3 focuses on Thermal Hydraulics and Safety and as the first activity, the pre-conceptual design of SCW-SMR has been proposed [8]. This pre-conceptual design is based on previous experience related to the development of SCWR and ensuring passive residual heat removal by natural convection. Among the main features of this pre-conceptual design are the significantly shorter fuel assemblies (FA) with horizontal placement and seven heat-up stages.

A lot of activities were dedicated to heat transfer along corroded surfaces. This involved improving and optimizing models and system codes, all done hand in hand also in cooperation with WP2. Figure 5 shows an example of newly produced experimental data focused on the effect of surface roughness on heat transfer. The 3D map of smooth and rough surfaces accompanies it.

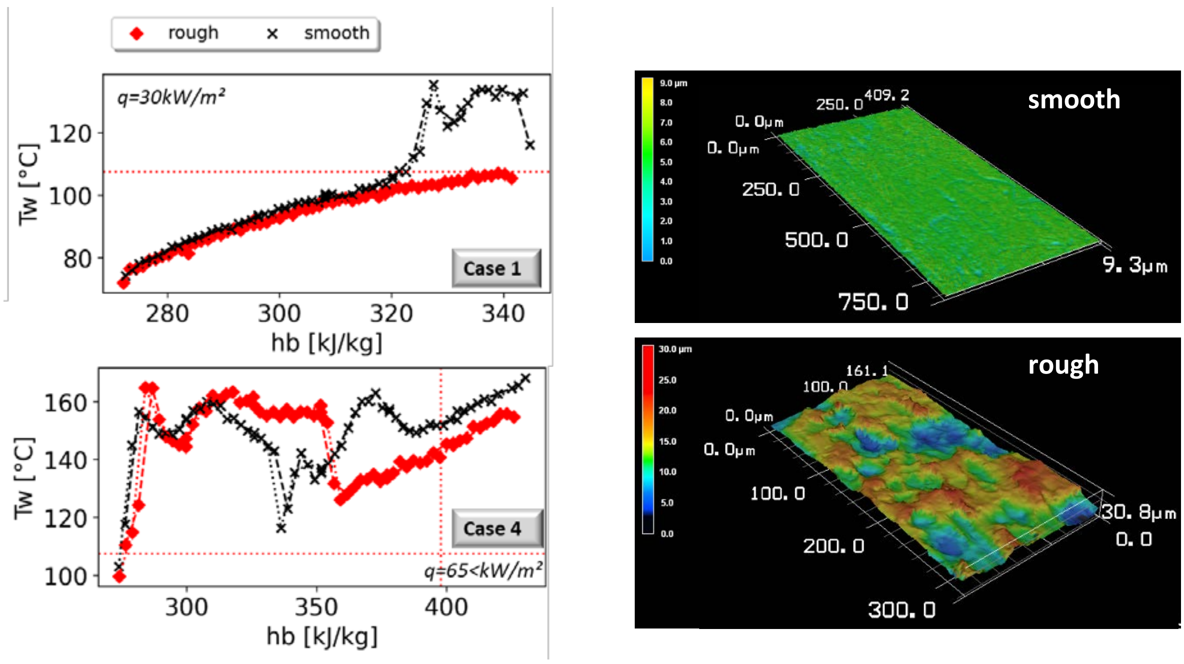


Figure 5: Newly generated experimental data for heat transfer to supercritical pressure R134a (left) revealing the effect of the surface roughness and the 3D maps of smooth and rough surfaces.

The existing correlations taking wall roughness into account were thus tested against the experimental data [9]. The assessment of those correlations indicated that further improvements are needed. The main ambition of WP3 is to derive the European-Canadian-Chinese (ECC) design requirements for an ECC SCW-SMR design concept involving some of the safety analysis as a basis for a future conceptual design project.

Within the WP, design- and safety-related neutronic parameters and reactor physics behaviour of SCW-SMR are studied to support the pre-conceptual design [8]. Thus, core models were developed with special attention to the reactivity reserve, achievable cycle length (over 2 years without shuffling) and power distributions with the highest power generation in the first few heat-up stages as shown in Figure 6 (left) [10].

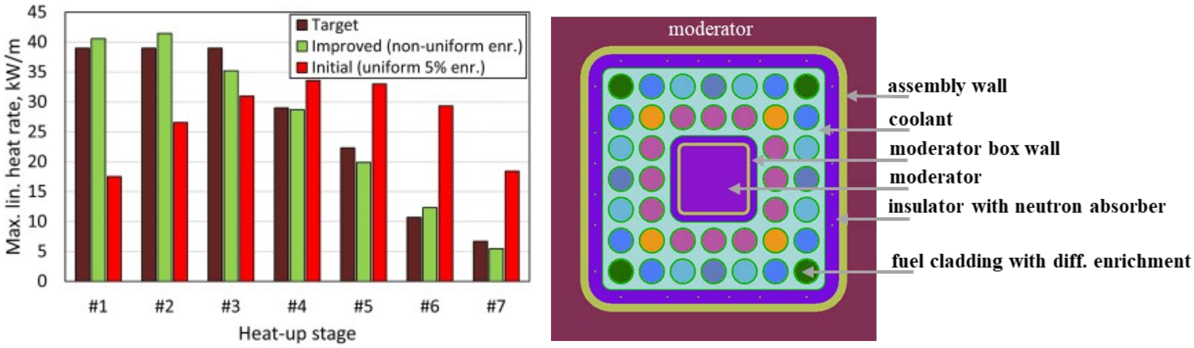
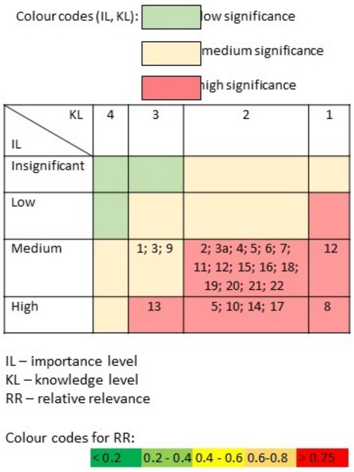


Figure 6: Left: MLHR (maximum linear heat rate) profile of the non-uniform enrichment model compared to the target profile and to the original model with uniform 5% enrichment [10]. Right: assembly fuel loading pattern made of six different enrichments, ranging from 5.0% to 8.2% (average 7.1%), and 24 B4C rods embedded in the assembly insulator [11].

Various coupled Apros - Serpent 2 calculations have been performed with UO_2 and UO_2-MOX mixed cores in order to extend the campaign and make the reactor more competitive. The calculations rely on detailed models with hot/cold/average assemblies and axial segmentation.

The introduction of inlet orifices proved to be an effective solution to reduce the maximum cladding temperature. A preliminary study was carried out on the possible use of burnable absorbers. Interesting results were obtained with an assembly fuel loading pattern made of six different enrichments, ranging from 5.0% to 8.2% (average 7.1%), and 24 B_4C rods embedded in the assembly insulator (Figure 6 (right).

WP5 called Synthesis & Guidelines For Safety Standards, focuses on developing generic and specific safety criteria and requirements for the SCW-SMR concept. WP5 syntheses the main safety-related findings and conclusions of the technical work packages 2, 3 and 4. For this purpose, the PIRT (Phenomena Identification Ranking Table) has been established and further analyzed (Figure 7).



WP2 – Ranking matrix

ID	Phenomen	IL	KL	RR
1	Through wall penetrations produced by general or localized corrosion	2.00	2.71	0.37
2	Oxide build-up that impedes heat transfer	1.57	2.29	0.60
3	Oxide release from the cladding surface	2.00	2.50	0.43
3a	Oxide release by dissolution / evaporation	1.83	2.17	0.57
4	Pellet cladding interaction	1.57	1.83	0.75
5	Environmental Assisted cracking (EAC)	1.29	2.29	0.67
6	Changes in the mechanical properties of the materials produced by ageing and/or irradiation	1.57	2.14	0.65
7	Changes in the geometry of tubes produced by irradiation, creep	2.29	1.86	0.53
8	Radiolysis processes	1.29	1.43	1.00
9	Physicochemical properties of water within the SC region	1.86	2.86	0.35
10	Resistance of cladding materials under LOCA conditions SCWR	1.29	1.57	0.94
11	Impurity enrichment	1.86	1.86	0.66
12	Oxide release from the cladding surface by spalling	1.57	2.00	0.70
13	Irradiation embrittlement due to He	1.29	2.71	0.50
14	IASCC	1.29	2.14	0.72
15	Hydriding	2.29	2.14	0.46
16	Cladding collapse	2.00	2.00	0.57
17	Overheating of the Cladding	1.43	2.00	0.74
18	Overheating of Fuel Pellets	1.86	2.33	0.51
19	Cladding rupture	1.86	2.14	0.57
20	Fuel Rod Mechanical Fracturing	2.00	1.83	0.62
21	Strain Fatigue	2.00	1.83	0.62
22	Fretting Wear	2.33	2.29	0.41

Figure 7: An example of PIRT analysis for WP2 [12].

Currently, European legislation is not yet tailored to address the specific features of SMR technologies, as it primarily focuses on large power units like EPR and VVER-1000. Current nuclear standards lack provisions for supercritical applications, including high pressure, high temperature, and the combination with neutron irradiation. To integrate SMRs into the European NPP portfolio, the graded approach and the practical elimination concepts should serve as starting points. Particular attention must be given to probabilistic and deterministic analyses, supported by a robust experimental campaign, even for reactors that could be situated near municipalities. Additionally, defining passive systems remains an open issue within European legislation.

3 CONCLUSION

The SCW-SMR merges the benefits of small modular design with supercritical water-cooled technology, targeting high thermal efficiency, reliable passive safety, flexible power generation, and reduced capital costs. While retaining the multi-pass coolant approach from the HPLWR reactor, this concept introduces shortened, horizontally oriented fuel bundles and increases the number of coolant heat-up stages to seven, reducing power peaking and enabling passive heat removal.

The success of ECC-SMART has been conditioned by the tight cooperation among technical work packages which contributed to the real progress. The achieved results have been summarised and described in the proposed Deliverables and Milestones according to the grant Agreement. Plenty of open access scientific papers describing results of ECC-SMART have been published. The international cooperation is crucial for knowledge transfer, motivation of the young researchers and making real progress in future innovative nuclear technologies. As the effective collaboration between a new generation of scientists and well-experienced experts is fruitful and can bring new scientific breakthroughs, the ECC-SMART has fulfilled the aims beyond the grant agreement's outputs.

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REFERENCES

[1] W.H.J. Graus, M. Voogt, E. Worrell, International comparison of energy efficiency of fossil power generation, Energy Policy. 35 (2007) 3936–3951. https://doi.org/10.1016/j.enpol.2007.01.016.

[2] ECC-SMART, ECC-SMART project, (b.r.). https://ecc-smart.eu/.

[3] M. Kryková, T. Schulenberg, M. Arnoult Růžičková, A. Sáez-Maderuelo, I. Otic, S. Czifrus, L. Cizelj, G.L. Pavel, European research program on supercritical water-cooled reactor, J. Nucl. Eng. Radiat. Sci. 7 (2021) 1–5. https://doi.org/10.1115/1.4048901.

[4] International Atomic Energy Agency, Advances in Small Modular Reactor Technology Developments, (2014) 150.

[5] D. Guzonas, R. Novotny, S. Pentilla, A. Toivonen, W. Zheng, Materials and Water Chemistry for Supercritical Water-cooled Reactors, 1st ed., Woodhead Publishing, United Kingdom, 2018. https://doi.org/10.1016/B978-0-08-102049-4.00005-2.

[6] R. Novotný, The 4th Project Meeting of ECC-SMART; WP2, (2024).

[7] J. Valtr, P. Roztočil, D. Dašek, R. Mušálek, F. Lukáč, J. Klečka, M. Janata, M. Arnoult-Růžičková, E. Mištová, L. Jelínek, P. Sajdl, J. Macák, Measurement system for in-situ estimation of instantaneous corrosion rate in supercritical water, J. Supercrit. Fluids. 204 (2024) 4–11. https://doi.org/10.1016/j.supflu.2023.106091.

[8] T. Schulenberg, I. Otic, Concept of a small modular SCWR with horizontal fuel assemblies, ASME J. Nucl. Rad Sci. 8 (2022). https://doi.org/10.1115/1.4052191.

[9] F. Wiltschko, M. Sipova, J. Vit, ICONE31-135141, in: Conf. Proc. ICONE31, Prague, 2024: s. 1–9.

[10] C. Antók, S. Czifrus, V. Giusti, Neutronic calculations for preliminary core design of SCW-SMR, Ann. Nucl. Energy. 209 (2024). https://doi.org/10.1016/j.anucene.2024.110805.

[11] S. Czifrus, The 4th Project Meeting of ECC-SMART; WP4, (2024).

[12] L. Cizelj, A. Prošek, M. Uršič, J.-C. de la Rosa Blul, O. Martin, A. Kiss, I. Boros, M. Hrehor, A. Toivonen, A. Nava-Dominguez, S. He, I. Otic, Safety criteria and requirements for the SCW-SMR concept., 2021. https://cordis.europa.eu/project/id/945234/results.