STATUS OF THE H2020 MCSAFER PROJECT-EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS FOR THE SAFETY EVALUATION OF WATER-COOLED SMRS

V. H. SANCHEZ-ESPINOZA[1], S. GABRIEL[1], H. SUIKKANEN[2], V. VALTAVIRTA[3], M. BENCIK[4], S. KLIEM[5], C. QUERAL[6], A. FARDA[7], P. SMITH[8], P. VAN UFFELEN[9], M. SEIDL[10], CH. SCHNEIDESCH[11], D. GRISHCHENKO[12], H. LESTANI[13]

[1]Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[2]LUT School of Energy Systems/Nuclear Engineering, Lappeenranta, Finland
[3]VTT, Espoo, Finland
[4]UJV Rez a.s., Rez, Czech Republic
[5]Helmholtz-Zentrum Dresden-Rossendorf, Rossendorf, Germany
[6]Department of Energy and Fuels, Universidad Politécnica de Madrid (UPM), Spain
[7]CEA, Paris, France
[8]JACOBS, Dorchester, UK
[9]European Commission, Joint Research Centre (JRC), Karlsruhe, Germany
[10]PreussenElektra GmbH, Hannover, Germany
[11]Tractebel Engineering S.A., Brussels, Belgium
[12]KTH Royal Institute of Technology (KTH), Stockholm, Sweden
[13]Comision Nacional de Energia Atomica (CNEA), Buenos Aires, Argentina

Abstract

The paper presents the main technical goals of the H2020 project entitled "High-performance advanced methods and experimental investigations for the safety evaluation of generic Small Modular Reactors (McSAFER)". The focus is on both numerical tools based on multi-physics and multiscale methods for SMR-safety investigations and on the experimental program at three European facilities, namely the COSMOS-H at KIT, HWAT at KTH, and MOTEL at LUT, where safety-relevant thermal hydraulic experiments for the core and helical heat exchanger are performed. The different safety analysis methodologies are applied to four water-cooled SMR-designs (CAREM, SMART, F-SMR, and NuScale), specifically to evaluate the core, reactor pressure vessel and plant behaviour under selected transient conditions (REA, Boron dilution, ATWS, and MSLB). The paper will describe the current status of the numerical and experimental investigations and will discuss selected results. The dissemination and education and training activities of the project will also be mentioned and an outlook provided.

1. INTRODUCTION

Small Modular Reactors (SMRs) of different type and size are being developed worldwide [1], [2], and [3]. Also in Europe, the deployment of e.g. water-cooled SMR is considered in different countries as part of the energy mix. Hence, both experimental and analytical research activities devoted to safety-related issues have been started at different institutions. It is also reflected by numerous European funded research projects to different kind of SMRs e.g. the ELSMOR [4], ECC-SMART [5], McSAFER [6], etc. In this context, the McSAFER project focuses on numerical simulations with different approaches to assess SMR-core and -plant behaviour under accidental conditions and on experimental investigations of safety-relevant thermal hydraulic phenomena. The simulation tools are based on the multi-physics and multi-scale approaches applied the first time to SMR-core, to the Reactor Pressure Vessel (RPV) and to the plant. They consist of solvers for neutron transport, thermal-hydraulic and fuel thermo-mechanic as well as their interdependencies. In McSAFER, the behaviour of four water-cooled SMR-designs such as the CAREM, SMART, French SMR (F-SMR), and NuScale under selected accidental conditions e.g. Rod Ejection Accident (REA) for NuScale and SMART, Cold Water Injection transient for CAREM, and F-SMR, Boron Dilution transient for NuScale, Anticipated Transient Without Scram (ATWS) for SMART, and Main Steam Line Break (MSLB) for NuScale and SMART will be investigated with the different simulation approaches. The McSAFER experimental program includes three European facilities: **C**ritical Heat Flux **O**n **S**mooth and **MO**dified **S**urfaces-**H**igh Pressure Loop (COSMOS-H) at KIT, **H**igh- pressure **WA**ter **T**est (HWAT) at KTH, and **MO**dular **TE**st **L**oop (MOTEL) at LUT, where key thermal hydraulic experiments for the core and helical heat exchanger will be performed.

In this paper, the status of different multi-physics / multi-scale methods under development by the different partners for the analysis of the SMR-core and -plant is described. In addition, first results of the experimental investigations of the McSAFER test facilities are discussed, which includes three facilities (MOTEL, COSMOS-H and HWAT) to investigate safety-relevant thermal hydraulic phenomena in the core, reactor pressure vessel and heat exchanger of integrated SMR-concepts. Selected results are presented and discussed.

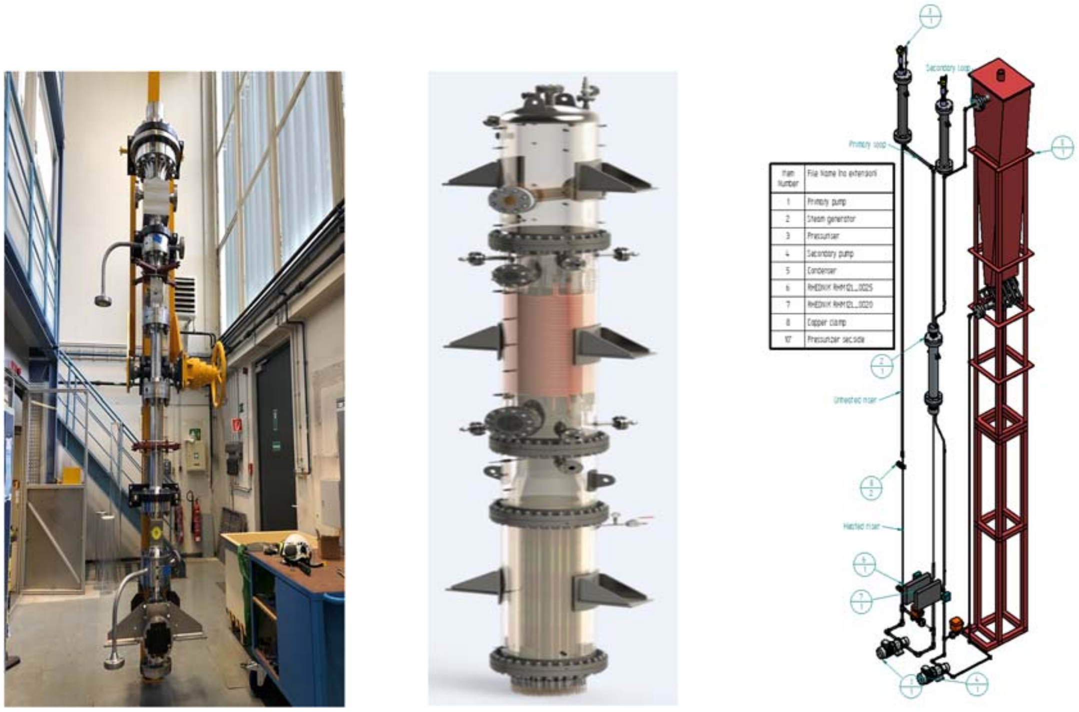
2. RESEARCH GOALS OF MCSAFER PROJECT

The High-performance advanced methods and experimental investigations for the safety evaluation of generic Small Modular Reactors (McSAFER) project is a research and innovation project funded by the Horizon 2020 research program of the European Commission. McSAFER started in September 2020 and will last until August 2023. Thirteen partners from nine countries form the Consortium. The main objective of McSAFER is, first of all, to provide new experimental data gained in three different facilities (at KIT, KTH, and LUT) under conditions relevant for light-water cooled Small Modular Reactor (SMR)-concepts. Moreover, the purpose of the project is to compare different safety analysis methodologies (industry-like standard methods, advanced and high-fidelity numerical tools) to analyse the behaviour of the core, the Reactor Pressure Vessel (RPV) and the integral plant under selected transient conditions [6]. The safety evaluations focus on four SMR-concepts: the French boron free F-SMR, the Argentinian CAREM system based on natural circulation and hexagonal core, the US NuScale design, and the Korean SMART reactor. The advanced numerical tools selected for the safety investigations are based on multi-scale (RPV and plant) and multi-physics (core) methods developed partly in former European projects, such as NURESAFE, HPCM and McSAFE. Beyond the involvement of industry (PEL, JACOBS, TRACTEBEL) and research centres (VTT, CEA, HZDR, UJV, CNEA), universities (KIT, KTH, LUT, UPM) are also engaged. The universities foster the education and training (master and doctoral students) and dissemination activities of the knowledge generated inside the project. The McSAFER project is structured around six Work Packages (WP) – WP2, WP3, WP4 and WP5. The WP6 is devoted to dissemination, exploitation and communication and a last one is devoted to project management (WP1).

3. STATUS OF THE EXPERIMENTAL INVESTIGATIONS AND VALIDATION UNDER MCSAFER PROJECT

3.1. Status of the experimental investigations

All three experimental facilities (COSMOS-H, MOTEL and HWAT) were built and the commissioning tests were successfully performed. Additional tests were necessary for the calibration of the instrumentation and for checking of the different sensors (pressure, temperature, mass flow, etc.). Detailed descriptions of the facilities are given in the deliverables [7], [8], [9], Fig. 1.



COSMOS-H (KIT) **MOTEL (LUT)** **HWAT Test Loop (KTH)**

Fig. 1: Experimental facilities of the McSAFER Project

These valuable information is needed by the partners involved in the code validation using the McSAFER experimental data. Hereafter, the status of the experimental investigations at each facility is given:

- COSMOS-H: The pressure hull of the test section including sub-systems were build and commissioned in October 2021. The test sections for the first and the second test series are designed and manufactured. Necessary pipelines of the test loop are manufactured, the heating for the steam lines installed and commissioned. Due to COVID, the delivery of some necessary parts has delayed the finalization and commissioning of the complete facility. In the meantime, most of the delayed parts have arrived and the test loop with the connection to the test track including the safety system are ready. Additional test with X-ray were done recently. Finally, the pressure test for the entire high-pressure system at 32.8 MPa was successful. The first test series will be started in the next weeks. The experimental program comprises: Fundamental heat transfer experiments at the COSMOS-H facility [7] using a heated tube in an annular gap and a heated rod bundle (five tubes) of dimensions similar to the ones of SMRs, to study Critical Heat Flux (CHF) phenomena for three different pressure levels (from 5 to 15 MPa). The preparation of the first test series at COSMOS-H are ongoing, where the test section consists of a single heated tube made of Zircalloy-4 arranged in an annular gap with an outer glass tube. The heat transfer between the cladding and the coolant is measured for an increasing heat flux. It ranges from subcooled boiling up to critical heat flux conditions.

- MOTEL: The facility is designed for SMR-relevant tests and includes essential components of SMR, e.g., helical coil heat exchanger, core, and pressurizer similar to NuScale) [8]. This facility was successfully commissioned in autumn 2020 and key-experiments to determine the pressure and heat losses were performed at the beginning of 2021, based on which the facility got the operating license. Description of the facility alongside detailed drawings were prepared and compiled to enable the construction of thermal hydraulic calculation models of the facility. Two test series are performed within McSAFER. One dedicated to the behaviour of the helical steam generator and another one to the core cross-flow phenomena. The first tests series focusing on the heat exchanger behaviour at different steady states with different core power levels was successfully performed in autumn 2021 [10]. The test series consisted of two experiments with four different steady state steps in each, the first experiment with heating powers of 250 kW, 500 kW, 750 kW and 1000 kW, while the second experiment was conducted with heating powers of 75 kW, 100 kW, 125 kW and 150 kW, Fig. 2. The maximum heating power of the MOTEL facility is 1000 kW. The facility behaviour was observed to be more stable in the second experiment with lower power levels. The description of the experiments and results can be found in [10]. Detailed test data was archived into the LUT experiment data storage (EDS) system, through which partners can access the data.

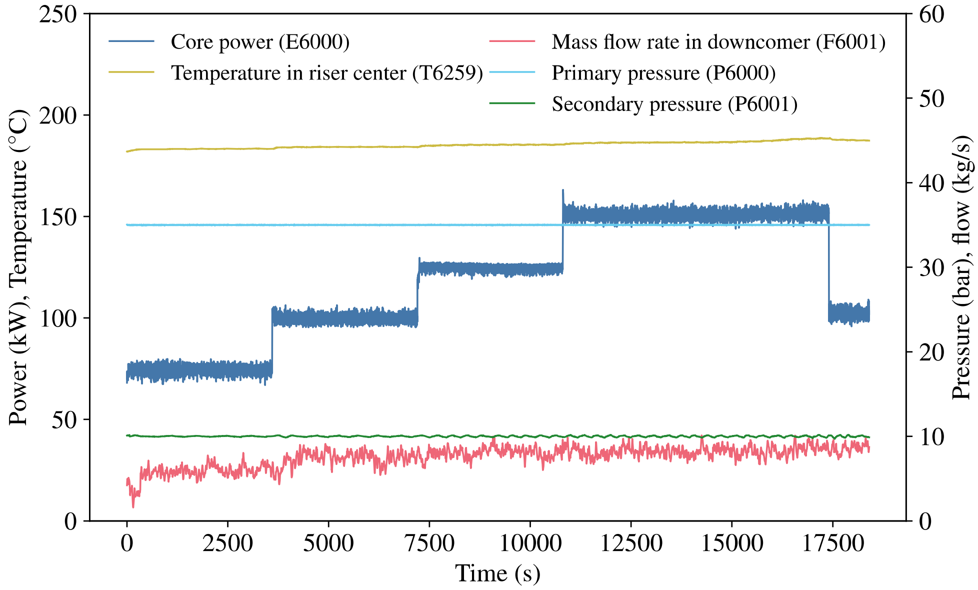


Fig. 2: Measurement data from the MOTEL MS-SG02 steam generator experiments. Four steady-state steps were conducted with the core heating powers 75 kW, 100 kW, 125 kW and 150 kW as shown by the blue curve

In Fig. 3, the axial temperature distribution of the primary side steam generator measured at four different power levels during the MS-SG02-test is shown. The first results have shown that the MOTEL facility behaves as expected.

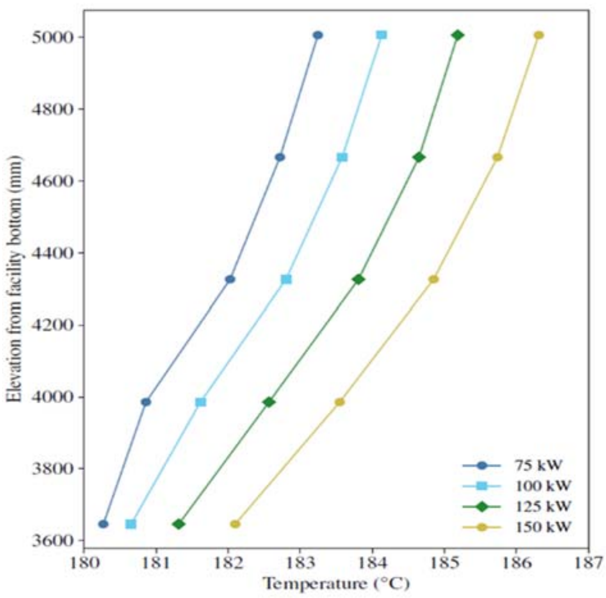


Fig. 3: Primary side steam generator axial temperature profiles with different core power levels during the MS-SG02 experiment.

- HWAT: At this facility, two-phase heat transfer tests under forced circulation and the transition to natural convection, considering SMR-relevant thermal hydraulic conditions, are planned. The investigations are focused on the study of heat transfer for subcooled boiling and CHF, the appropriateness of two critical components (heated riser and pool type condenser) for relevant transient tests [9]. The design of the experimental setup, definition of the test matrix and pre-test calculations, Fig. 4, for the first test series of the HWAT experiments were conducted during autumn 2020 and the beginning of 2021. The construction of the test loop was finalized and commissioning tests were performed during the autumn 2021. During the commissioning tests, a leak was found in some loop components caused by misalignment between the sealing surface and threads axis from the manufacturing, which required re-design, re-machining and replacing the faulty items. After the repairs, the commissioning tests were successfully completed in September 2021. Experiments were initiated but during October and November 2021, further component faults were detected in the pneumatic feed-water pump and the rheostat used with the HWAT 1 MW power generator. These component failures required further inspections and replacement parts. The component faults caused delay to the completion of the first experiments. The preparations for the second test series were started in parallel to the remaining work for the first test series. This work included the design of key loop components, such as the heat exchanger and the pressurizer, discussions with a workshop for manufacturing, the procurement of other necessary equipment and design simulations and scoping analyses.

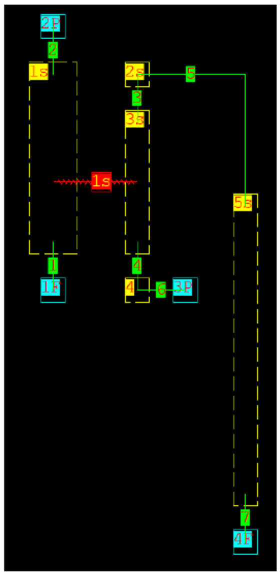


Fig. 4: Multi-sensor probe unit of the HWAT facility (left) and GOTHIC model of HWAT for pre-test analyses (right).

3.2. Status of validation of thermal hydraulic codes using McSAFER-data

Within the McSAFER-project unique safety-relevant thermal hydraulic experiments at three European facilities will be performed. The measured data is very much appropriate to validate thermal hydraulic codes of different type e.g. Computational Fluid Dynamics (CFD), subchannel and system thermal hydraulic codes. These SMR-relevant data will allow the validation of key-models of the numerical tools for the prediction of important safety margins e.g. DNBR, etc. Hereafter a list of codes are listed which will be validated using the data of the different McSAFER-facilities:

- COSMOS-H: ANSYS-CFX, OpenFOAM, Subchanflow (SCF), VIPRE, TRACE, RELAP3D
  Status: validation calculations, preliminary work for critical heat flux modelling and preparation of the OpenFOAM calculation model was done at LUT and a preliminary RELAP5-3D model of the single tube in annular gap arrangement was prepared at UJV
- MOTEL: ANSYS-CFX, FLUENT, VIPRE, COBRA-TF, APROS, TRACE
  Status: validation calculations, an initial APROS model of the primary side of the MOTEL facility was prepared at LUT. An initial subchannel input deck of the MOTEL core was prepared at TBL for COBRA-TF. At UJV, preparation of a CFD model in FLUENT was started and a preliminary calculation mesh was established, Fig. 5. Also, the preparation of the VIPRE subchannel model of MOTEL was started at UJV.
- HWAT: OpenFOAM, GOTHIC, TRACE

Status: validation calculations, pre-test calculations with GOTHIC were performed at KTH for both the first and second test series. TRACE model of the HWAT first test series was elaborated and first calculations are performed by UPM.

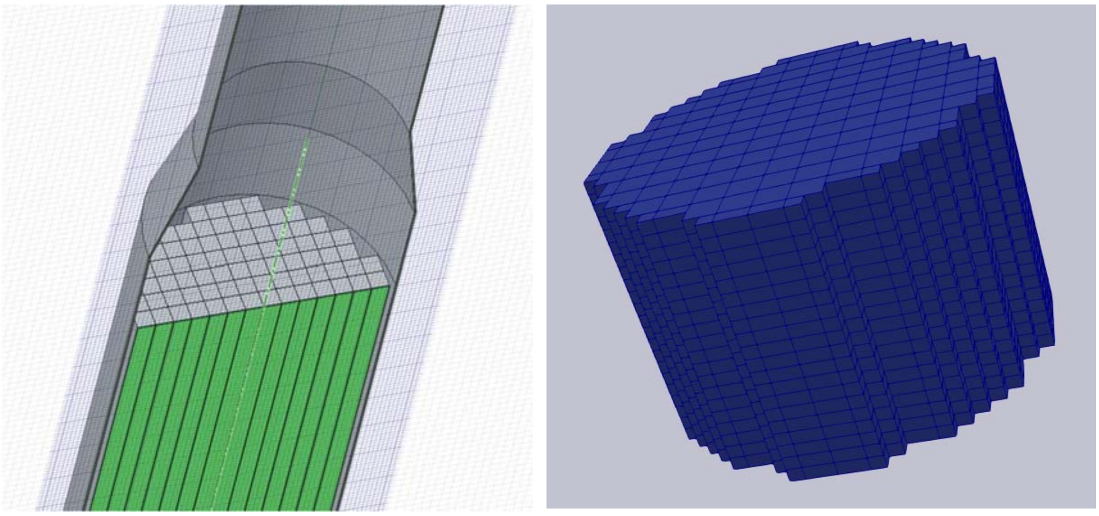


Fig. 5: FLUENT CFD model prepared by UJV (left) and COBRA-TF model prepared by TBL (right) for the MOTEL facility.

4. STATUS OF THE MULTI-PHYSICS CORE ANALYSIS

The multi-physics core analysis for four SMR-core designs e.g. CAREM, F-SMR, KSMR, and NuScale are performed with different computational routes as listed below:

- Traditional codes based on 1-D system TH and Point-kinetics: RELAP5, ATHLET, TRACE
- 1D system TH with 3D nodal diffusion: TRACE/PANTHER, TRACE/PARCS, SIMULATE-S3K, ANTS/TARCE, PUMA/SCF
- Low order transport including subchannel TH-codes: PARCS-SP3/SCF, APOLLO3/FLICA, WIMS/ARTHUR, DYN3D-SP3/SCF
- High-fidelity MC with subchannel TH- and TM-codes: SERPENT2/SCF/TRANSURANUS

The main reason for the consideration of different simulation approaches is to demonstrate the advances of more precise core analysis methods, show their complementarity and finally identify the best methods for SMR-cores. Due to the peculiarity of the SMR-cores such as their compactness, heterogeneity, complex control rod designs, etc. it is mandatory to apply different approaches starting with 2-group diffusion, multi-group diffusion, transport, and Monte Carlo solutions. Within McSAFER, two scenarios were selected to be analysed for the different designs: 1) Rod ejection accident for NuScale and KSMR and 2) Cold water injection for CAREM and F-SMR designs. The generation of the nuclear data libraries for the different simulations are generated with lattice physics codes (deterministic and Monte Carlo) taking into account the geometrical and material data and operational conditions of the different SMR-cores. The analysis with coupled nodal diffusion codes of the mentioned transients is in an advanced stage while the high-fidelity simulations are under preparation (SP3 transport and Monte Carlo). The problem definition and geometrical/material details of the investigated cases are summarized in [1] while the cross section generation methods for the different solvers (diffusion and transport are given in [2] and [3]. The current status of the multi-physics core analysis can be summarized as follows:

- The NuScale core is analysed with Serpent2/DYN3D (HZDR), Serpent2/ANTS/SCF(VTT), WIMS/PANTHER/VIPRE01 (TBL), CASMO/SIMULATE5/SK3 (PEL) and Helios/DYN3D (UJV). The comparison of selected parameters for REA showed that the different codes predict similar trends. The reasons for the deviations are discussed in detail in the deliverables [4]. One of the reasons for the expected discrepancies are related to the different physical modelling approaches of the different neutronics and thermal hydraulic solvers. Based on the obtained results by the different codes for NuScale it can be stated that all steady state integral parameters are in reasonable agreement. Nevertheless, SIMULATE shows somewhat higher Critical Boron Concentration (CBC) and ejected CRW and noticeably lower SCRAM worth compared to the other solutions. DYN3D and ANTS (research codes) show a slight tilt towards the core centre for the nominal radial power distribution compared to Panther and SIMULATE (industry codes), Fig. 6. The maximum difference between two groups of codes is about 3.3%. A similar tendency can be observed for the radial power distribution after the ejection of the RE2 CRA. All codes show consistent agreement in prediction of radial power distribution of the shutdown core.

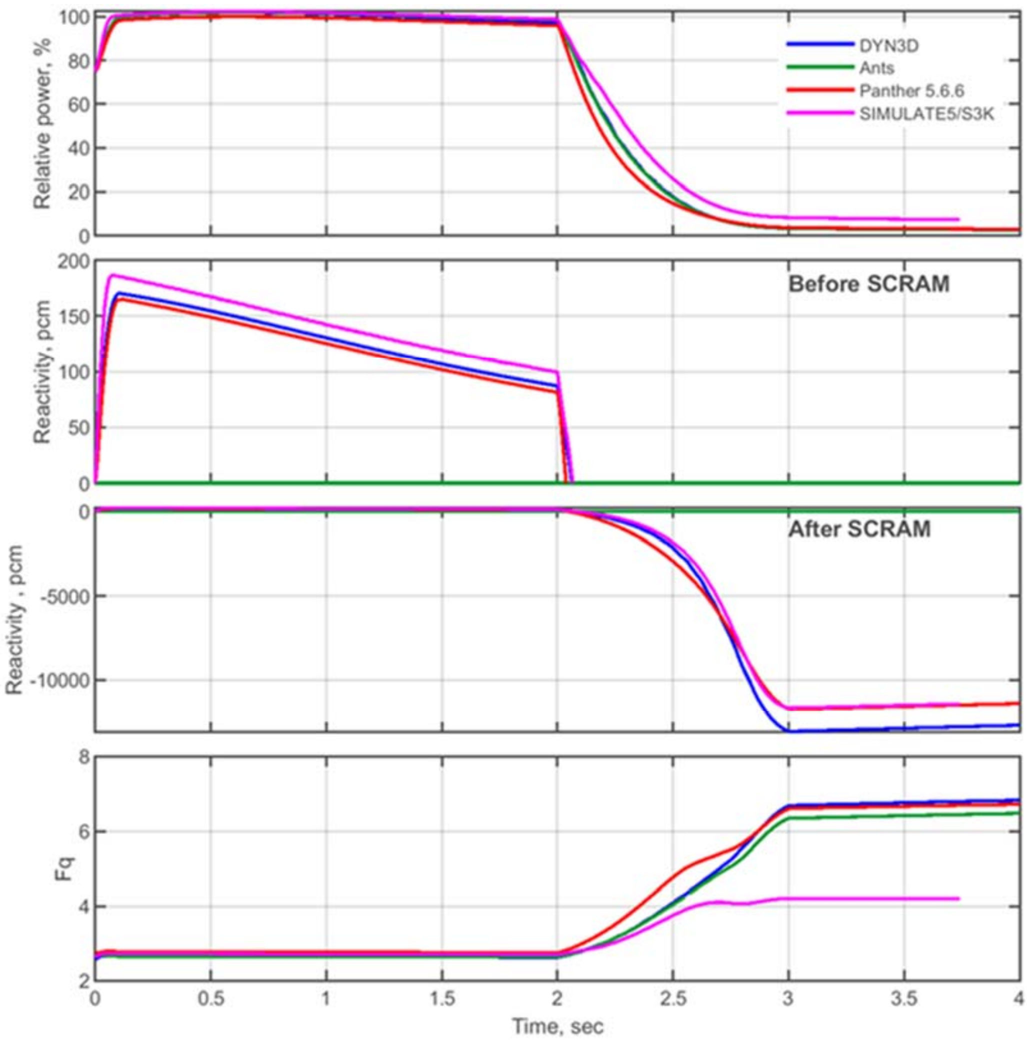


Fig. 6: NuScale REA Analysis using different simulation approaches

- For the CAREM and F-SMR reactor, the cold water injection transient is considered since the REA is excluded by design. The CAREM-core was analysed by both KIT using Serpent/PARCS/ICoCo/SCF (KIT) and by CNEA using the Huemul/CONDOR/SCF computation tools, Fig. 7. The differences of the code predictions are stemming from the different approaches for the generation of condensed nodal cross sections using the deterministic (HUEMUL) and the stochastic (Serpent) approach [4].

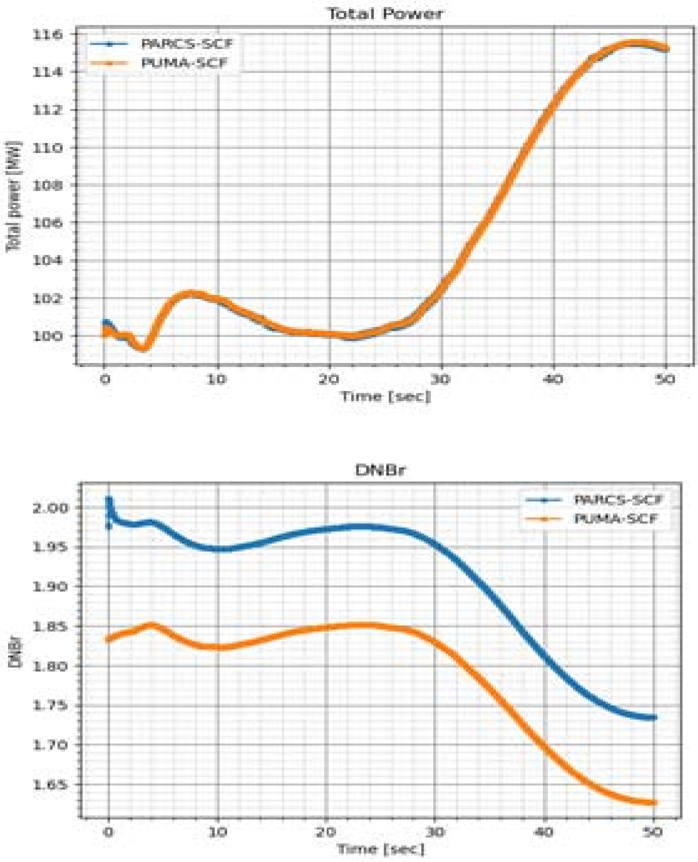


Fig. 7: CAREM: Analysis of the cold water injection transient with two different simulation approaches: Predicted total power (top) and DNBR (bottom) evolution by two different computational approaches

It is worth to mention that a new transient decay heat model was added to Serpent2 to account for the thermal energy deposition during transient calculations by implementing a group-based decay heat curve-fitting methodology [5]. This model was implemented and tested in Serpent2. Finally, the specifications for a SMR-core loaded with ATF-fuel loading are finalized [6]. This ATF-loaded core will be analysed using high-fidelity coupled codes such as Serpent2/SCF/TRANSURANUS.

5. STATUS OF MULTI-PHYSICS AND -SCALE ANALYSIS OF THE RPV AND THE INTEGRAL SMR-PLANTS

In the McSAFER-project, improvement of the simulation of three-dimensional thermal hydraulic phenomena within the RPV of integrated SMR-designs is achieved by applying multiscale thermal hydraulic tools in addition to the traditional ones i.e. 1D thermal hydraulic system codes. Doing so, the spatial resolution of the computational domains is increased to achieve a higher prediction accuracy compared to the ones of 1D coarse mesh codes.

In a first step (Work package 4) only the behaviour of the RPV of the NuScale and SMART reactors using boundary conditions at the RPV-inlet and outlet in case of a boron dilution (NuScale) and the Anticipated Transient Without Scram (SMART) is analysed with different methods (traditional and multiscale approach). The multiscale approach considers the following coupling options:

- Multi-scale coupling of system and subchannel thermal hydraulic codes and
- Multi-scale coupling of CFD and system thermal hydraulic codes.

In a second step (Work package 5), the behaviour of the integral NuScale and SMART plants is analysed with multi-physics and multi-scale coupled codes for the steam line break accidents.

In both steps, different computational routes will be applied and the obtained results will be compared to each other in order to demonstrate the advantages of the new approaches compared to the traditional ones and also to show their complementarity. The following simulation approaches are used in McSAFER:

- 1-D system TH + 3D nodal diffusion codes: TRACE 1D/PARCS (UPM), TRACE 1D/PANTHER (TRACTEBEL), TRACE/ANTS (VTT)
- 3D system TH + 3D nodal diffusion + subchannel codes: TRACE/PARCS/Subchanflow (KIT, UPM), TRACE/WIMS/ARTHUR (Jacobs)
- 3D system thermal hydraulic + 3D nodal diffusion + CFD codes: TRACE/PARCS/OpenFOAM (KIT, UPM), ATHLET/DYN3D/TrioCFD (HZDR), ATHLET/DYN3D/FLUENT(UJV), TRACE/OpenFOAM/ANTS (VTT).

1D and 3D thermal hydraulic models of the SMART [7] and NuScale [8] SMRs are developed. These models are a prerequisite for multi-scale coupled code analysis of selected transients. The performed steady state calculations for both SMART and NuScale design show a very good agreement with the values published in the open literature. The simulation of the ATWS-scenario for the SMART reactor as well as the one for the boron dilution scenario of NuScale are mostly completed. In Fig. 8, the evolution of the power and the core averaged coolant temperature as predicted by TRACE 1D (TBL) and 3D (KIT) models for the ATWS are compared to each other. In general, the global trends are very similar, [7].

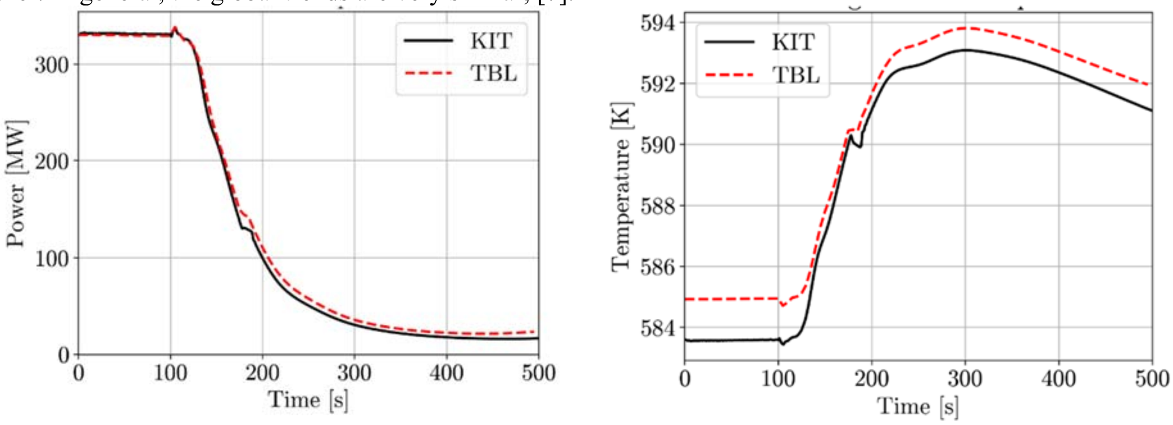


Fig. 8: SMART SMR: Comparison of the power and core averaged coolant temperature predicted by 1D (TBL) and 3D thermal hydraulic model (KIT) using the TRACE code.

The investigations considered in step-1 are well advanced [9] while the investigations for the step-2 has been started recently with the developments of the input models for the involved codes and with the testing of the different coupling schemes developed by the partners. In Fig. 9, the NuScale thermal hydraulic model developed by the UPM for TRACE is shown (left). For the multiscale simulation of NuScale, the core was also modelled with SCF. A coupled TRACE/SCF simulation was performed. In Fig. 9 (right) the predicted coolant temperature in the core and the core mass flow rate (bottom right) is shown for the stationary plant conditions

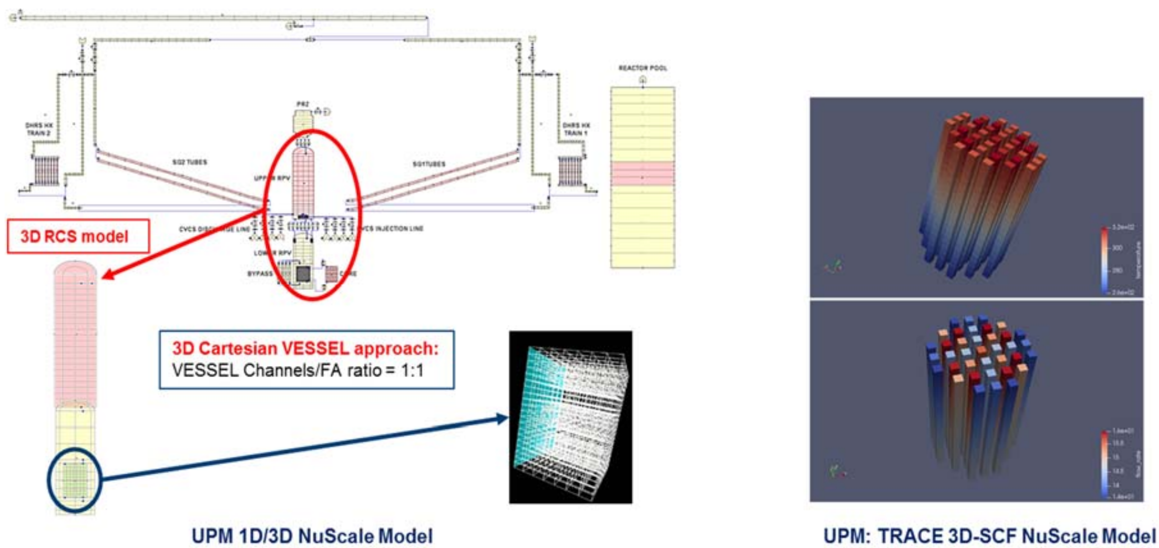


Fig. 9: Integral TRACE model of NuScale (left). Predicted coolant temperature (top right) and core mass flow rate (bottom right) as predicted by the multiscale system TRACE/SCF coupled with ICoCo (right)

The respective CFD-models of parts of the reactor pressure vessel of NuScale and SMART are in advanced stage of development for the multi-scale/multi-physics simulations of the steam line break transients to be analysed in the near future.

6. CONCLUSIONS AND FUTURE WORK

In general it can be stated that the McSAFER project is progressing as expected with some delays in performing tests at COSMOS-H and HWAT due to the delays in deliver of parts for the facilities. The core analysis with multi-physics coupled codes is advanced while the multiscale analysis of the behaviour of the integrated RPV under boron dilution (NuScale) and ATWS (SMART) conditions has been started. For the final multi-scale/ multi-physics analysis of the MSLB-accidents of NuScale and SMART, the corresponding models of the integral plants for the system thermal hydraulic codes and neutron kinetics core simulators are developed and under testing.

The focus of the investigations for the remaining time of the McSAFER-project is on the following areas:

- Perform the planned experiments at the COSMOS-H and HWAT facilities
- Evaluate and document the two test series performed successfully at the MOTEL-facility devoted to the behaviour of the helical HX and the cross-flow inside the core
- Extensive validation of the different thermal hydraulic codes (CFD, subchannel and system TH) using data of the McSAFER-facilities
- Finalization of the multi-physics/-scale analysis of the ATWS (SMART) and boron dilution (NuScale) accidents
- Finalize the multi-physics/-scale analysis of the MSLB both NuScale and SMART reactors

Based on the status of the project it can be stated that the consortium will successfully finalize the research program in the foreseen timeframe without delays.

ACKNOWLEDGEMENTS

The authors would like to acknowledge all researchers involved in McSAFER for their valuable contributions summarized in the paper. The McSAFER project has received funding from the European Union's Horizon 2020 Research and Innovation program under grant agreement number 945063.

REFERENCES

[1] OECD, "Small Modular Reactors: Challenges and Opportunities. NEA Nr. 7560," OECD, Paris, 2021.

[2] IAEA, "Small Modular Reactor (SMR) Regulator's Forum," IAEA, 2021. [Online]. Available: https://www.iaea.org/topics/small-modular-reactors/smr-regulators-forum. [Accessed 23.08.2021 August 2021].

[3] IAEA, "Optimization of the Coupling of Nuclear Reactors and Desalination Systems," IAEA, Vienna, 2005.

[4] ELSMOR, "Towards European Licencing of Small Modular Reactors," EU, 1 September 2019. [Online]. Available: https://cordis.europa.eu/project/id/847553/reporting/fr. [Accessed 25 Mai 2022].

[5] ECC-SMART, "Development of Small Modular Reactor Technology," ECC-SMART, 1 September 2019. [Online]. Available: https://ecc-smart.eu/. [Accessed 25. Mai 2022].

[6] V. H. Sanchez-Espinoza, S. Gabriel, H. Suikkanen, J. Telkkä, V. Valtavirta, M. Bencik, S. Kliem, C. Queral, A. Farda, F. Abéguilé, P. Smith, P. V. Uffelen, L. Ammirabile, M. Seidl, C. Schneidesch, D. Grishchenko and H. Lestani, "The H2020 McSAFER Project: Main Goals, Technical Work, Program, and Status," Energies, vol. 6348, p. 14, 2021.

[7] S. Gabriel, G. Albrecht, W. Heiler and F. Heineken, "COSMOS-H experimental setup and tests," McSAFER. Deliverable Number 2.1, Karlsruhe, 2021.

[8] K. Tielinen, J. Telkkä, E. Kotro, V. Kouhia and H. Suikkanen, "Description of the MOTEL facility and instrumentation," McSAFER. Deliverable 2.4, Helsinki, 2021.

[9] D. Grishchenko, "HWAT experimental setup and test matrix for first test series. D2.7," McSAFER Project , Stockholm, 2021.

[10] J. Telkkä, A. Räsänen, E. Kotro and H. Suikkanen, "Results of the MOTEL helical coil steam generator behaviour experiments (D2.5)," LUT, Helsinki, 2021.

[11] V. Ville, F. Anthime, F. Emil, L. Héctor and M. Luigi, "Specifications for the reactivity transients scenarios in the four SMR cores," McSAFER. Deliverable NUmber 3.1, Helsinki, 2021.

[12] E. Fridman, D. Ferraro, V. Valtavirta, H. Lestani, L. Mercatali, R. Vocka, Y. Bilodid, M. Seidl and A. Fard, "Group constant generation for the state-of-the-art codes," McSAFER. Deliverable Number 3.2, Dresden, 2021.

[13] A. Farda, L. Mercatali, K. Zhang, V. Sanchez-Espinoza, Y. Bilobid, and A. Charles, "Group constant generation for pin level advanced solvers. D3.5," McSAFER, Karlsruhe, 2021.

[14] E. Fridman, Y. Bilodid, M. Dalinger, H. Lestani, E. Lopasso, A. Weir, R. P. Salazar, J. Blanco, L. Mercatali, V. Sanchez, A. Farda, V. Valtavirta, A. Jambrina, M. Seidl, D. D. Meyer and H. F. R. Vocka, "Stat-of-the-art solutions for th transient scenarions in the four SMR-cores. D3.4," McSAFER, Karlsruhe, 2022.

[15] A. Jambrina and V. Valtavirta, "Transient decay heat model for Serpent. D3.7," McSAFER, Helsinki, 2022.

[16] P. van Uffellen, "Specifications for the SMR-core with ATF-loading. D310," McSAFER, Karlsruhe, 2022.

[17] N. Palmans, J. Etcheto and M. Garcia, "Analysis of tthe SMART plant with 1D system code and intercomparing between codes. D4.1," McSAFER, Karlsruhe, 2020.

[18] O. Parera-Villacampa, L. Ammirabile, C. Queral, J. Sanchez-Torrijos, K. F. Cosials and V. Jammont, "Analysis of the NuScale plant with 1D systemcodes and intercomparing between codes. D4.2," McSAFER, Brüssels, 2022.

[19] M. Garcia and N. P. J. Etcheto, "Analysis of SMART plant with 3D system thermal hydraulic codes (D4.3)," McSAFER, Karlsruhe, 2022.