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Project Report

The H2020 McSAFER Project: Main Goals, Technical Work Program, and Status

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Abstract: This paper describes the main objectives, technical content, and status of the H2020 project entitled "High-performance advanced methods and experimental investigations for the safety evaluation of generic Small Modular Reactors (McSAFER)". The main pillars of this project are the combination of safety-relevant thermal hydraulic experiments and numerical simulations of different approaches for safety evaluations of light water-cooled Small Modular Reactors (SMR). It describes the goals, the consortium, and the involved thermal hydraulic test facilities, e.g., the COSMOS-H (KIT), HWAT (KTH), and MOTEL (LUT), including the experimental programs. It also outlines the different safety assessment methodologies applied to four different SMR-designs, namely the CAREM (CNEA), SMART (KAERI), F-SMR (CEA), and NuScale. These methodologies are multiscale thermal hydraulics, conventional, low order, and high fidelity neutron physical methods used to demonstrate the inherent safety features of SMR-core designs under postulated design-basis-accident conditions. Finally, the status of the investigations is shortly discussed followed by the dissemination activities and an outlook.

Keywords: SMR; multiphysics; multiscale; high fidelity; safety evaluations; experiments

1. Introduction

The interest on the development and deployment of Small Modular Reactors (SMR) has in the last years expanded worldwide, including Europe. Many studies have been carried out in different European countries, e.g., Poland, England, France, and Estonia to discuss the potential technical and economic feasibility of SMR deployment as a part of the energy grid together with large nuclear power plants and renewables [1]. Some European countries have advocated that SMRs must be a part of the future energy mix to achieve the low-carbon power generation goals with low risk and cost in a competitive energy market. Other countries, e.g., Finland, are actively discussing the use of dedicated SMRs characterized by low operating temperature and pressure for district heating, an option that has also been considered in countries with an existing district heating network, such as Poland [2].

Furthermore, the International Atomic Energy Agency (IAEA) is developing many activities to support the Member States' needs regarding the development and deployment of SMR to complement the energy mix [1]. The goal of the SMR Regulators' Forum is, for example, to identify, understand, and address the key regulatory challenges for SMR licensing (e.g., working groups on a graded approach, defense-in-depth, and emergency planning zone) [2]. The water-cooled SMR concepts are more advanced and are already in the certification and/or pre-licensing phase, e.g., in NuScale [3], mPower [4], IRIS [5], SMART [6], and CAREM [7] than the liquid-metal cooled and gas-cooled SMR concepts.

From a safety perspective, different SMR concepts based on LWR technology are equipped with similar features to ensure important safety functions such as core sub-criticality and core coolability (short and long term) that mainly rely on passive systems. The inherent safety features are determined by the core design, i.e., the choice of the core size, core power density, material composition, and fuel rod arrangement with or without boron addition to the coolant [6,7]. The simple and modular PWR SMRs integrate innovative heat exchangers [8], pumps, and pressurizers inside the Reactor Pressure Vessel (RPV). On the contrary, in the RPV of a modular BWR only the core, the separators/dryers (depending on the design), and the pumps are included.

The removal of short and long-term residual heat relies mainly on natural circulation and passive residual heat removal systems (PRHRS) developed for Gen-III power reactors such as AP-1000, ESBWR, AES-92, AES-2006, HPR1000, APR+, and KERENA. Emergency Core Cooling systems (ECCS) are mainly passive and consist of Core Makeup Tanks (CMTs), accumulators, gravity drain from tanks, and passive recirculation from containment sumps combined with an Automatic Depressurization System (ADS). The new features of SMR concepts aims at improving the plant safety by combining robust inherent core safety features with passive systems for both short and long-term heat removal.

On the other hand, the design simplifications are expected to substantially reduce the construction time and cost, as well as the cost for operation, maintenance, and repair. Under the described conditions and constructive peculiarities of an integrated RPV-concept, the thermal hydraulic phenomena inside the RPV are characterized by a multi-dimensional flow perturbed by the in-vessel components placed around the core [9]. Consequently, a mixed convection flow under normal or accidental conditions may exist, where the coolant mixing inside the Reactor Pressure Vessel (RPV) plays a key role in case of component failure, e.g., if one of the steam generators or a pump fails [4]. The usefulness of legacy codes based on 1D thermal hydraulics models is very limited. Instead, the use of multi-dimensional numerical tools and novel approaches is mandatory [10–18].

The new core designs, the integral concept, the innovative heat exchangers, the passive heat removal systems, as well as the novel containment designs, represent new challenges for safety demonstration in the frame of a licensing process in the near future. The majority of SMR cores have a small number of fuel assemblies ranging from 37 to 60. The active core height is shorter (between 1.4 and 3.7 m) compared to the core of a conventional PWR, where the reflector' designs play a more important role.

In the particular case of the boron-free core designs, to address the problem of potentially large axial power peaking factors, the optimization of the core loading and of the control rod design needs to be addressed. These factors have led to a more heterogeneous core loading and to the use of different control rod materials (SS, AIC, and/or B4C).

1.1. Challenges for Numerical Tools

These core design peculiarities challenge the prediction capability and accuracy of the legacy analysis tools (nodal diffusion solvers coupled with 1D thermal hydraulic codes) since the diffusion theory relies on modelling approximations not always fully applicable for such core configurations. These new design trends emphasize the needs for high fidelity solutions. Higher order solutions based on neutronic transport solvers (deterministic and stochastic) coupled with subchannel thermal hydraulics are currently envisaged, while Computational Fluid Dynamics (CFD) might come into play in the longterm. Such advanced simulation tools are expected to enhance the prediction of local safety parameters of modern core loadings of LWR and SMR, etc., taking into account local feedbacks in the frame of advanced pin-by-pin/subchannel level core simulations.

The high-fidelity multiphysics tools are a promising alternative to the legacy codes used to describe the neutronic, thermal hydraulics, and thermo-mechanic behavior of SMR cores under stationary or transient conditions, since they rely on transport solvers (stochastic) coupled with quasi-3D subchannel codes. The McSAFE simulation tools pave the way for high fidelity and resolution simulations, i.e., the pin-by-pin and subchannel levels taking into account the local feedbacks of involved physic domains.

Key regulatory challenges of LWR-cooled SMR concepts for deployment in the near future have been discussed in the past [19] and are being studied and reviewed in the frame of a H2020 project (ELSMOR) [20] that started in 2018 for four years. Hence, the McSAFER research is fully complementary to the ELSMOR project in its addressing of the technical challenges for core and Reactor Pressure Vessel (RPV) analysis.

1.2. Advanced Tools for Safety Evaluations

The high-fidelity simulation tools, including neutronics, thermal hydraulics, and thermo-mechanics developed within the previous H2020 McSAFE-project, which relies on highly accurate Monte Carlo neutronic solvers and subchannel thermal hydraulics, are very promising in predicting the key safety parameters at the pin level of Light Water Reactor (LWR) cores using High-Performance Computer (HPC) clusters. These achievements pave the way for the static and time-dependent simulations of SMR cores considering local thermal hydraulic feedbacks. They also provide reference solutions for low-order simulations based on, e.g., diffusion solvers coupled with 1D system thermal hydraulic codes representing the core as a set of parallel channels, which are nowadays the main tools accepted in licensing processes, thanks to their extensive qualification and validation.

In addition, advanced transport approximation methods are under development in different countries [21,22], where the nodal diffusion solvers are replaced by deterministic transport solvers and the 1D thermal hydraulic codes are being replaced by 3D-coarse mesh of system codes or subchannel codes, and, in some cases, thermo-mechanics codes for fuel rods are also coupled to them. The fuel performance simulations tools also enable the consideration of accident-tolerant fuel materials that are under development.

Finally, the different tools being developed for the core and plant analysis of SMRs need a comprehensive validation using appropriate data relevant to SMRs.

1.3. Validation of Numerical Tools

The validation of numerical simulation tools is an important precondition for their use by both industry and regulators. Hence, in the McSAFER project, selected thermal hydraulic experiments are performed at different laboratories (LUT, KIT, KTH) using SMR-relevant mock-ups ranging from fuel rod arrangements to a full reactor circuit model including all major components, such as helical heat exchangers. For neutronic parameters at the pin level, where no experimental data are available, the Monte Carlo-based high-fidelity simulations developed under the H2020 McSAFE project are used as a reference solution of nodal diffusion codes in combination with a pin power reconstruction or transport-based pin-by-pin simulations at both normal and accidental core conditions [23,24].

2. McSAFER Partners and Structure

The partners of the consortium and the structure of the project set-up to assure the achievement of the technical goals are described hereafter.

2.1. Project Partners

The McSAFER project is a research and innovation project with ca. EUR 4 million funding from the European Union Horizon 2020 research program. The project started in September 2020 and it will last for three years. The consortium consists of 13 partners from nine countries. It brings together different EU institutions, including research centers (VTT, HZDR, KIT, UJV, JRC KA, CNEA, CEA), industry (JACOBS, PEL, TRACTEBEL), and universities (LUT, KTH, KIT, UPM) engaged in the development of SMRs. They are also involved in the development of methods for the optimization of the design and enhanced safety and evaluations of SMR-specific issues, such as the design of small cores with or without boron, an integrated RPV-concept, innovative heat exchangers, passive heat removal systems, etc. Two partners (CNEA and CEA) are studying their own designs (CAREM and boron-free F-SMR). Industrial partners (TRACTEBEL, PEL, and JACOBS) have great experience in the safety analysis of LWRs and partly of SMRs.

The numerical simulation tools are mainly a part of the European NURESIM platform for reactor simulations, which is continuously being improved, extended, and consolidated. The partners are KIT (Coordination), VTT, CEA, HZDR, UJV, JRC, LUT, KTH, PEL, JACOBS, TRACTEBEL, UPM, and CNEA.

Four of the six partners from research institutions have been working together for many years in different EU Projects such as NURISP, NURESAFE, HPMC, and McSAFE. The involvement of four universities such as KIT, LUT, KTH, and UPM facilitates the engagement of students (master and doctoral students) in McSAFER. Moreover, it helps to disseminate gained knowledge through the organization of training courses, international workshops, online courses, etc. Figure 1 shows the positioning of McSAFER within European research activities related to numerical simulation tools for design optimization and safety assessment.

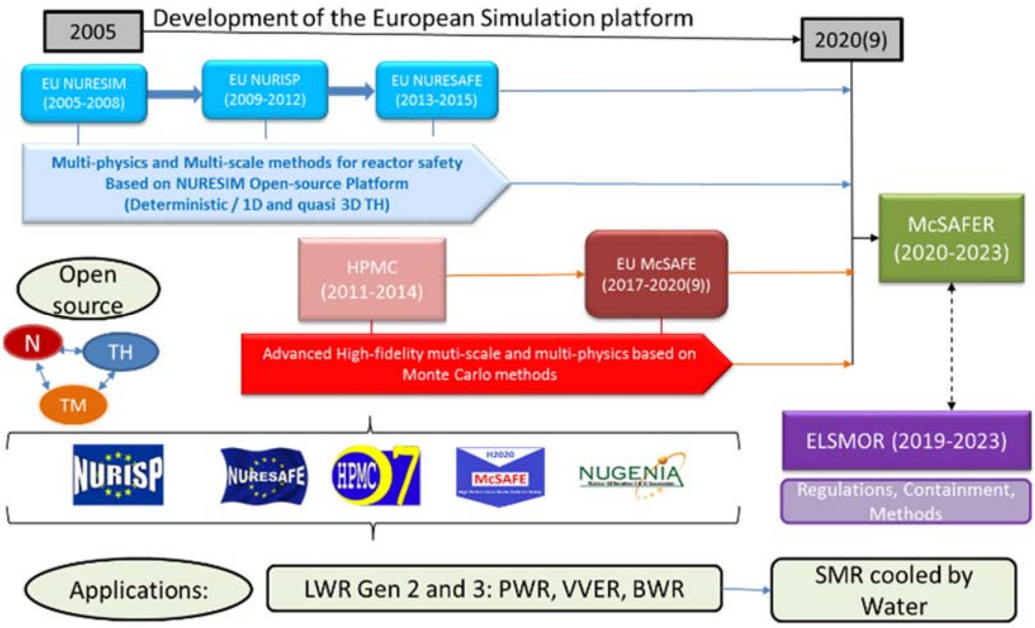


Figure 1. Roadmap for the McSAFER tools in the EU context.

2.2. McSAFER Structure

In order to achieve the above-mentioned objectives, the McSAFER project is organized in four technical work packages (WP2 to WP5): one for the dissemination, exploitation and communication of the outcomes of the consortium and one for project management. In Figure 2, the work packages and the interactions among them are illustrated.

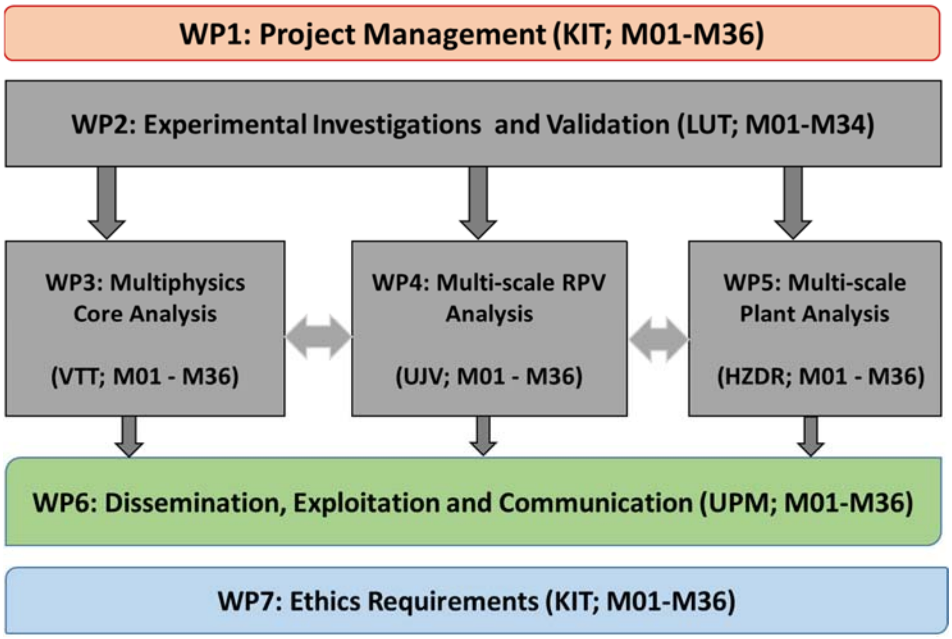


Figure 2. McSAFER work packages and their interactions.

The McSAFER project is implemented as a part of the continuous development of the European research activities that started in 2005, devoted to the development of a European simulation platform for reactor simulations based on multi-scale and multiphysics methods combining neutronics, thermal hydraulics, and thermo-mechanics. The McSAFER project is fully in line with its two predecessors, the FP7 HPMC and H2020 McSAFE projects [25], which are in the scope of the NUGENIA alliance. It is worth mentioning that NURESAFE, HPMC, and McSAFE paved the way for McSAFER. There are large intersections between the technical goals of McSAFER and the global technical goals of SNETP [26] and NUGENIA [27]. The main research topic of McSAFER reflects the research priorities of the SNETP and NUGENIA's strategic research and innovation agenda. Figure 1 shows the relation of the positioning of McSAFER within the European research activities related with numerical simulation tools for design optimization and safety assessment.

3. Main Goals and Content of the Technical Work Packages

The general goals of McSAFER in the European context are to provide advanced computational tools capable of performing safety analysis in accordance with the Western European Nuclear Regulators Association (WENRA) requirements and considering the specifications of national regulatory guidelines for the near-term deployment of SMRs in Europe. The numerical tools consist of advanced reduced-order safety analysis codes, complemented by high-fidelity multiphysics/multiscale numerical tools.

The advancement of the safety research for SMRs is achieved by combining experimental investigations and different numerical simulations. Hence, McSAFER focuses on the development, improvement, validation, and application of numerical simulation tools validated with experimental data generated within the Consortium at several facilities relevant for the majority of SMR-designs such as COSMOS-H (KIT), MOTEL (LUT), and HWAT (KTH).

Hence, the McSAFER-project demonstrates the advantages of using high-fidelity codes in practical licensing processes and the complementarity of low-order and high-order solvers to quantify and possibly reduce the conservatism of margins in safety demonstrations and enhance operational flexibility of SMRs in a mixed grid of carbon-free electricity generation.

Hereafter, the content of the four technical work packages and of the dissemination, exploitation, and communication work package are described.

3.1. Experimental Investigations and Validation

Key experimental investigations were planned in three European laboratories focusing on SMR-relevant phenomena in the core and in the reactor pressure vessel to provide data for code validation. The experimental program comprises:

- Fundamental heat transfer experiments at the COSMOS-H facility 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 CHF phenomena at three different pressure levels (from 5 to 15 MPa) [28].
- Experiments at the MOTEL facility, which is designed for SMR-relevant tests and includes essential components of SMR, e.g., a helical coil heat exchanger, core, and pressurizer (representative for NuScale). A test series is dedicated to investigate the behavior of the helical steam generator and another one to study the cross-flow phenomena [29].
- Tests at the HWAT facility including a two-phase heat transfer under forced circulation and the transition to natural convection considering SMR-relevant thermal hydraulic conditions.

Another important part of the work program is the validation of the thermal hydraulic codes (CFD, subchannel, and system thermal hydraulic) with the experimental data generated within the consortium to increase the confidence on the numerical tools used for safety demonstration:

- Validation of CFD codes using the experimental data of COSMOS-H, MOTEL, and HWAT.
- Validation of subchannel thermal hydraulic codes with the experimental data obtained with the proposed tests.
- Validation of system thermal hydraulic codes using the test data generated.

In Figure 3, the different thermal hydraulic tests facilities of McSAFER are shown.

The Critical Heat Flux on Smooth and Modified Surfaces–High Pressure Loop (COSMOS-H) facility consists of a high-pressure circuit for fully demineralized water and two circuits connected in series with thermal oil and a cooling brine [28]. The key parameters are as follows: System pressure in the range of 5 to 17 MPa, maximal coolant temperature 360 °C, maximal power 1.8 MW (600 kW for the test section) and a mass flow rate up to 1.4 kg/s. This allows for the achieving of SMR-relevant conditions with a scale of 1:1 for CAREM, NuScale, and SMART. The test section has a diameter of 80 mm and the heater can be equipped with a large number of thermocouples from the inside and pressure sensors at the inlet and outlet. Since the test section track has inspection glasses, the phenomena inside can be observed using high-speed cameras and laser technology.

The experimental program consists of the following test series:

- Serie 1: Tests with a single Zircaloy tube in an annular gap of 4 m height. Different CHF tests are foreseen in order to quantify the measurement uncertainty. In addition to sensors for pressure, temperature, and mass flow, imaging measurement techniques is also be used;
- Serie 2: Rod bundle experiments with five Zircaloy tubes arranged in a square geometry with one at the center. A tube length of 1 m has been considered. Only the methods based on the backscattering of light such as Laser Dopper Anemometrie (LDA) are used, since the optical accessibility is limited.

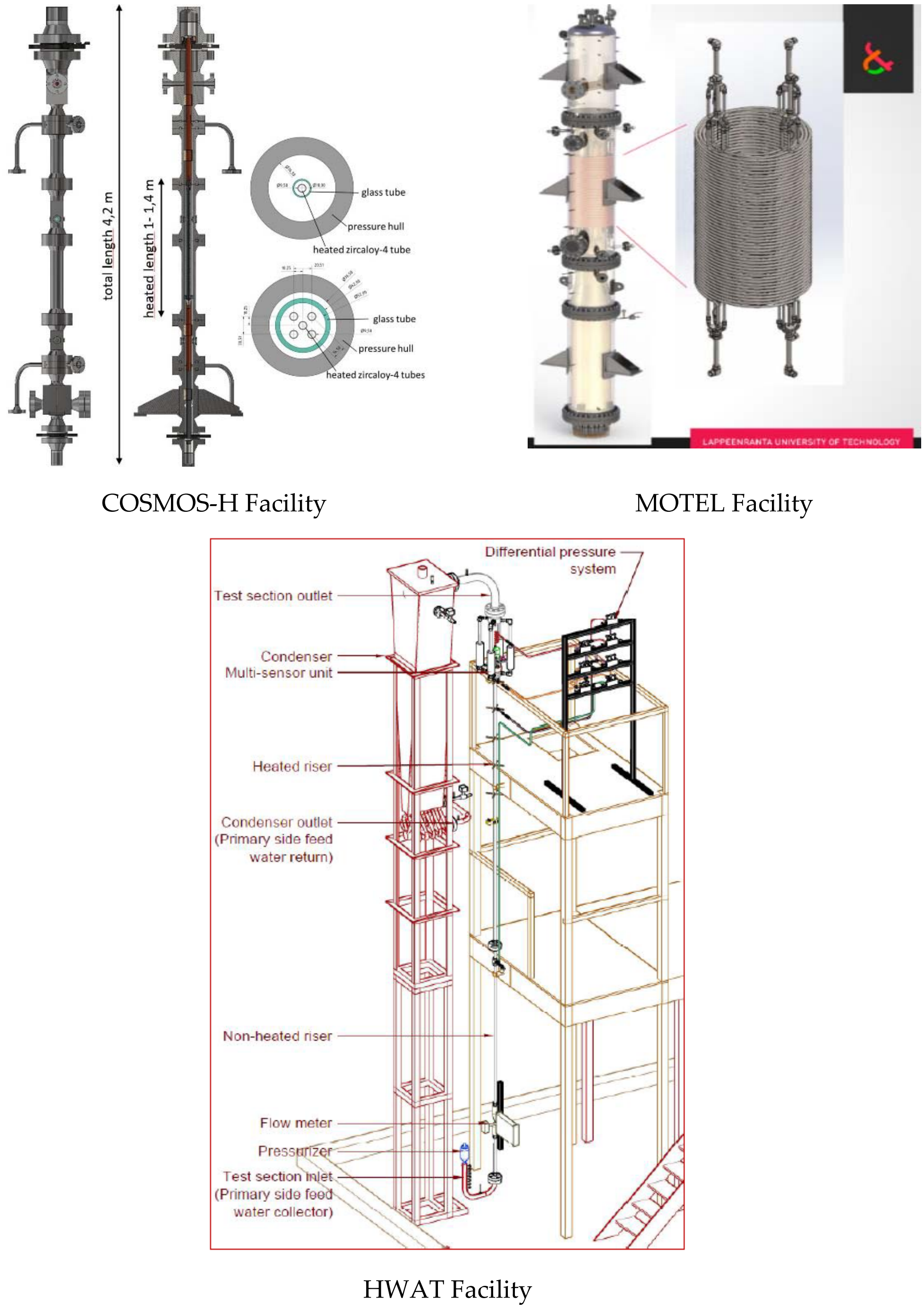


Figure 3. Test facilities of McSAFER consortium [28,29].

At the HWAT facility, two-phase heat transfer tests under forced circulation and transition from forced to natural circulation for SMR-relevant conditions are carried out. For this purpose, the facility is equipped with a downcomer (DC) heated riser, a movable multisensory unit to measure local void fraction, bubble size distribution, dynamic pressure and temperature, thermocouples to track Departure from Nucleate Boiling (DNB), and gauge and differential pressure measurements. Two test series are foreseen to be carried out:

- Forced circulation steady-state tests: measurement of the distribution of the flow with a multi-sensor probe, measurement of the heat transfer under different flow conditions inside the heater riser.

- Forced-to-natural circulation transients in a ca. 8.8 m high closed loop including the riser, a return line and a condenser test section. Transient local flow characteristics, natural circulation stability, and transient local flow characteristics during natural circulation are measured.

The MOTEL (MOdular TEst Loop) test facility is built to represent a typical integral PWR-type SMR, such as the NuScale [30]. It has a total height of around 7.7 m and a width of ca. 0.7 m. It consists of three changeable modules: core, steam generator, and pressurizer. The design pressure is 40 bars, the coolant temperature is up to 250 °C, and the maximum heating power is ca. 990 kW. The helical coil steam generator consists of four groups of tubes such as in NuScale, with an inner diameter of 15 mm and a wall thickness of 1.0 mm, resulting in a total heat transfer area of 17 m^2. The core comprises 132 heating rods with a heated length of 1830 mm and a diameter of 19.05 mm. In addition, there are 16 instrumentation rods, each of which include five temperature measurements at different levels. The radial power of the core can be adjusted in 12 regions, and the axial power distribution is five-stepped, mimicking the cosine shape of a real Nuclear Power Plant (NPP) core axial power distribution. Instrumentation of MOTEL is based on traditional point-form measurements, totaling over 340 thermocouples. Each SG tube has 3 temperature measurements (inlet, outlet, middle), and there are altogether 212 temperature measurement points in the core. Pressure is measured in the upper plenum of the primary side and in the steam collector of the secondary side. There are altogether seven pressure difference measurements in the facility. Other advanced measuring techniques applied are, for example, the ultrasonic flow meters that are used to measure the primary flow rate in the annular downcomer space. The MOTEL test program includes the following experiments:

- Series 1: MOTEL helical coil steam generator experiments to study the behavior of the helical coil SG, i.e., steady-state heat transfer, temperature distributions along the SG tubes, steady states with different power levels;
- Series 2: MOTEL cross-flow experiments: mixing between subchannels with even and skewed radial power distributions in the core by adjusting the powers of the 12 radial heating regions.

The main results of the tests are used for the validation of CFD and subchannel and system thermal hydraulic codes such as OpenFOAM, CFX, FLUENT, CTF, SubChanFlow, VIPRE, TRACE, RELAP5-3D, APROS, and GOTHIC.

3.2. Multiphysics Core Analysis

The third objective is the improvement of the reactor physics, thermal hydraulics, and thermo-mechanics simulations of SMR-cores under nominal and accidental conditions, e.g., Rod Ejection Accident (REA) and the demonstration of the complementarity of advanced and high-fidelity core analysis methods with the traditional ones when applied for licensing. Consequently, the following core analysis methods are applied for static and transient analysis:

- Develop advanced deterministic solvers (SP3-pin-by-pin/subchannel) for improving core analysis achieving higher prediction accuracy, i.e., at the pin-level compared to the traditional lower-fidelity codes (nodal solutions);
- Demonstrate the need for high-fidelity novel multiphysics and multiscale codes to improve the traditional low-fidelity codes and methods which are currently in use by both the industry and regulators for routine simulations;
- Show the appropriateness of the high-fidelity multiphysics solutions based on Monte Carlo methods developed within the McSAFE project as the reference solution for the reduced-order solutions, especially in cases where no experimental data are available;
- Extend the core analysis tools (neutronic, thermal hydraulic, and thermo-mechanics) for the simulation of a SMR core loaded with accident tolerant fuel (ATF).

In this work package, four SMR core designs (CAREM, F-SMR, KSMR, and NuScale) are investigated (Figure 4).

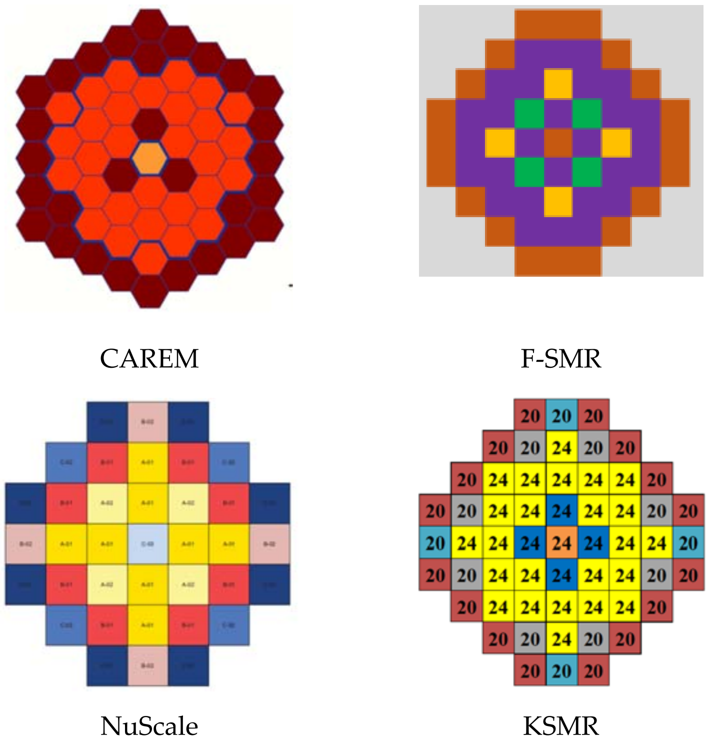


Figure 4. Schematic layout of the cores of four SMR-designs.

3.3. Multiscale Reactor Pressure Vessel Analysis

This work package is devoted to the improvement of the simulation of three-dimensional thermal hydraulic phenomena inside the reactor pressure vessel of the integrated SMR designs. This enhancement is pursued by using multiscale thermal hydraulic tools in combination with traditional ones by increasing the spatial resolution of the computational domains and thereby achieving a higher prediction accuracy compared to the traditional low-fidelity codes. Specifically, it includes:

- Selection of appropriate Design Basis Accident (DBA) sequences, e.g., steam line break, boron dilution, and Anticipated Transients Without Scram (ATWS);
- Application of multiscale thermal hydraulic methods, including the coupling of system thermal hydraulic and subchannel codes for the analysis of the RPV.
- Application of novel multiscale thermal hydraulic methods, including the coupling of CFD and system thermal hydraulic codes for the analysis of the RPV.

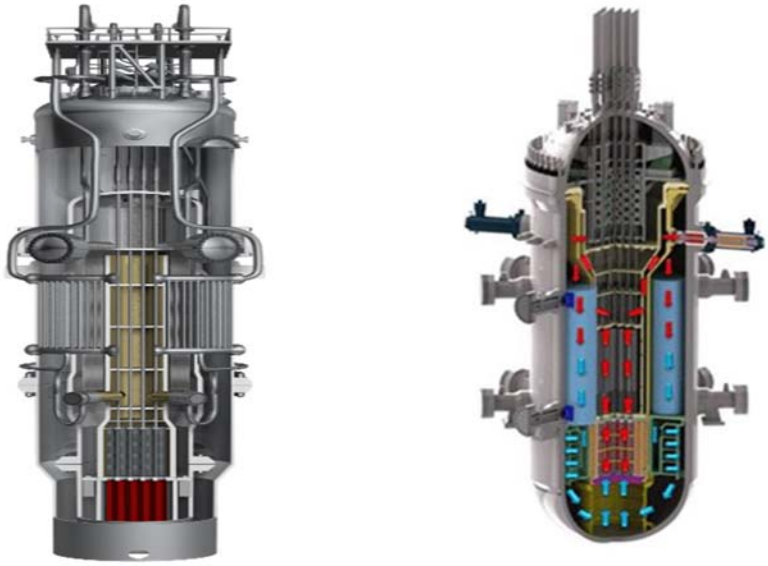
Different safety analysis methodologies are applied to the NuScale (natural nominal circulation) and the generic SMART RPV (forced nominal circulation) designs (Figure 5).

3.4. Multiscale Plant Analysis

The multiscale plant analysis is oriented to apply the improved and validated numerical tools for the analysis of selected accidents in SMR plants, e.g., SMART and NuScale, and compare the results with those produced by the traditional methods. For example, it includes:

- The selection of the SMR-relevant design basis accidents for the analysis with traditional methods, e.g., steam line break, ATWS, or boron dilution when applicable;
- The analysis of the selected design basis accidents using advanced safety analysis methodologies based on a multiscale and multiphysics approach;
- A comparison of the different safety analysis approaches.

The different safety analysis methodologies are applied to the NuScale (Figure 6) and the generic SMART plant.



NuScale RPV SMART RPV

Figure 5. Layout of the reactor pressure vessels of two SMR designs [31,32].

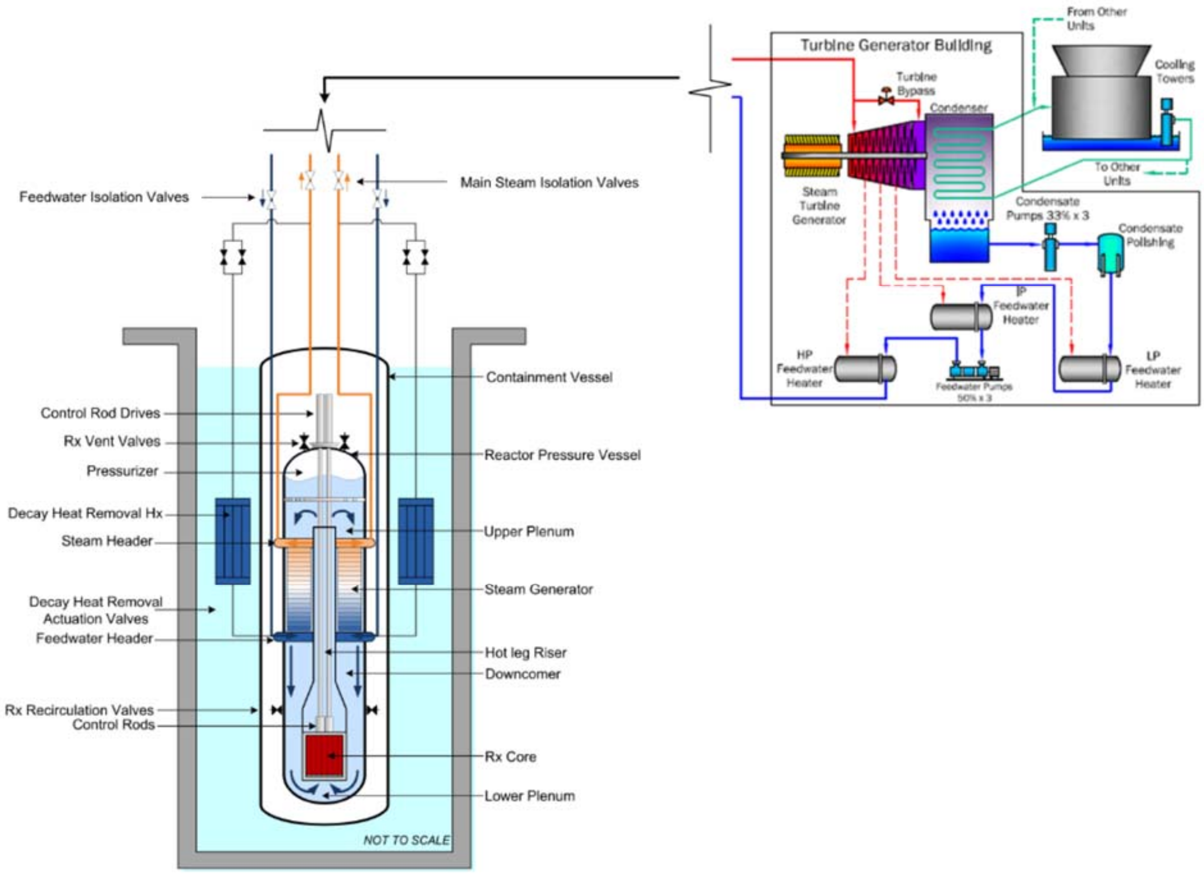


Figure 6. NuScale plant layout [31].

3.5. Dissemination, Exploitation and Communication

Based on the list of stakeholders identified as relevant to reach the McSAFER impacts, the consortium identifies a list of specific and targeted activities for the dissemination and exploitation of the project results. The coordinator with the "dissemination team" specifically created to support the coordinator fosters the dissemination of knowledge and the main results of McSAFER through the following actions:

- Organization of workshops;
- Dedicated training courses including massive open online course (MOOC).

For the exploitation of the McSAFER outcome in the near and medium term, the instruments for the dedicated exchange of information with the "targeted audience", i.e., the end-users' community (NUGENIA), about the maturity and prediction capability of the numerical tools and about the validation status are foreseen.

- Creation of a User Group (UG);
- Creation of a technical Advisory Board (AB);

The communication actions are focused on informing the scientific community, end-users, and stakeholders about the progress of the project. For this purpose, the following actions are foreseen:

- Public project website;
- Regular project Newsletter issues;
- Publications of Press releases;
- Presentations in conferences and publications.

The McSAFER project is planned as a research and innovation action. Despite the focus on the applications to SMRs, the methodology is fully applicable to LWRs of Gen-II and -III, as well as to Gen-IV reactors including research reactors, due to the versatility of the Monte Carlo methods.

4. Status of the Project

4.1. The Experimental and Validation Program

At month 10 of the project, the completion of the experimental set-ups, especially of the test section, the measurement devices, calibration of the instrumentation, adaptations and pre-testings at the three experimental facilities (COSMOS-H, MOTEL, and HWAT) are in an advanced stage of realization, paving the way for the first tests. It is important to highlight that the key-test parameters, e.g., pressure, velocity, heat fluxes, subcooling, and heated length are representative of the operating conditions of the SMR designs to be investigated in the project, such as NuScale, SMART, F-SMR, and CAREM. The first test series under preparation at the facilities include following tests:

- HWAT facility: Heat transfer for subcooled boiling and CHF; study of the appropriateness of two critical components (heated riser and pool type condenser) for future transient tests [33];
- MOTEL: The first test series are focused on the helical coil steam generator behavior. The primary/secondary heat transfer is studied on different steady states with different core power levels [34];
- COSMOS-H: The first test planned consists of a single heated tube made of Zircalloy-4 arranged in an annular gap with an outer glass tube [35]. The heat transfer between the cladding and the coolant is measured for an increasing heat flux. It ranges from subcooled boiling until critical heat flux conditions.

The first test results are expected at the end of 2021. Based on the information provided in the deliverables about the test facilities, the partners started to develop their input decks for the pre- and post-tests analysis for the different codes (CFD, subchannel, and system codes) for code validation purposes.

4.2. Multiphysics Core Analysis

Two deliverables (D3.1 and D3.2) are already finalized. The first one [36] describes the material, geometrical, and thermal hydraulic parameters of four SMR-cores needed to perform lattice physics simulations, i.e., for the generation of cross-sections for different core analyses (fuel assembly and pin level) and for the core analysis with different solvers (diffusion, SP3, collision probability, etc.,) but also for coupled Monte Carlo/subchannel thermal hydraulic core analysis of stationary and transient conditions. In addition, the transient scenarios to be investigated with different computational routes are described for the cores of CAREM, F-SMR, NuScale, and SMART. The second deliverable [37] summarizes the methodologies for the generation of neutronic group constants for both diffusion (DYN3D, PARCS, APOLLO3, SIMULATE S3K, ANTS, PUMA, and PANTHER) and transport solvers (PARCS-SP3, APOLLO3, and DYN3D-SP3) [36,37]. Additional deliverables about, e.g., the group constant generation at pin level for the transport solvers and the advanced heat deposition model, are expected at end of August 2021.

4.3. Multiphysics and Multiscale Reactor Pressure Vessel (RPV) Analysis

The development of the corresponding models of the RPVs of both SMART and NuScale has started by collecting the needed data and building a data base shared among the involved partners. Based on it, thermal hydraulic models with different spatial resolution are being built for different codes in order to analyze the selected accidental sequences, such as Boron dilution (NuScale), MSLB (SMART, NuScale), and ATWS (SMART). The models are developed for the following code categories:

- One-dimensional system thermal hydraulic codes (TRACE, ATHLET, RELAP5);
- Tridimensional system thermal hydraulic codes (TRACE, ATHLET-3D, RELAP-3D);
- Subchannel codes (SUBCHANFLOW, ARTHUR);
- CFD-codes (OpenFOAM, Fluent).

Different coupled versions of these thermal hydraulic codes are applied to evaluate the 3D thermal hydraulic phenomena inside the RPV and core of the selected SMR-designs. The first results of the simulation are planned for February 2022.

4.4. Multiscale Plant Analysis

For the multiscale analysis of the plant behavior under accidental conditions, complementary activities to the ones listed in Section 4.3. have started with the collection of data for the involved control and safety systems, and for the reactor control and protection system of each design (setpoints). The focus here is to develop plant models to be used by the different safety analysis approaches discussed in Section 3.4. In Table 1, different multiscale/multiphysics-coupled codes are considered for plant analysis.

Table 1. Numerical tools for the plant analysis of NuScale and SMART.

System TH-Codes	CFD-Codes	Core Simulator
ATHLET	FLUENT	DYN3D
ATHLET	OpenFOAM	DYN3D
TRACE	OpenFOAM	ANTS
TRACE	OpenFOAM	PARCS

The optimization and testing of the coupling approaches has started and the model developments of the two SMR-designs to be represented by the different codes is under preparation. The first results of the simulation are planned for June 2022.

4.5. Dissemination, Exploitation and Communication

The public website is ready (www.mcsafer-h2020.eu) (accessed on 12 August 2021). The first online training course was successfully carried out during the last week of January 2021. Around 140 participants from all around the world participated. Twelve of around fifty deliverables are public and will be uploaded to the public project webpage.

5. Outlook

The McSAFER project started in September 2020. The first experimental results are expected at the beginning of 2022. The preparatory work for the validation of different codes has already started. The analytical and numerical work is progressing according to the work plan. The data review and collection regarding the accidental sequences to be analyzed in the WP3, WP4, and WP5 is underway. In summary, it can be stated that, despite the conditions of the COVID-19 pandemic in the EU, the project is progressing without major delays.

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