IMPROVING SAFETY ANALYSIS METHODOLOGIES AND MOVING FROM TRADITIONAL TO HIGH-FIDELITY SAFETY ANALYSIS TOOLS FOR SMALL MODULAR REACTORS

McSAFER - NEWSLETTER 08/2023

Dear Colleagues,

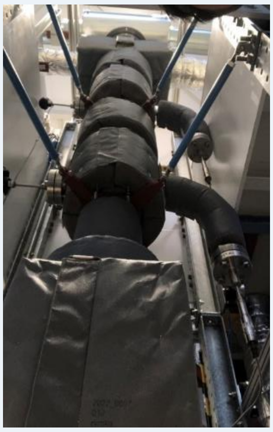
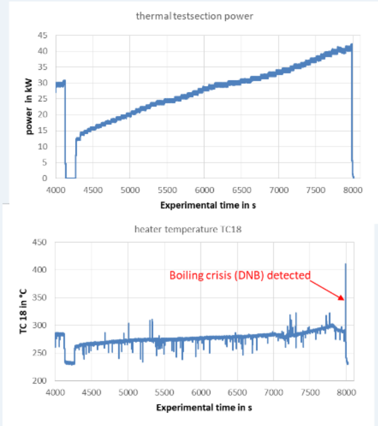
In the last year new and exciting results have emerged from our research. On June 19th-21st, the McSAFER consortium assembled for its 3rd Progress Meeting and we would like to take this opportunity to provide a brief glance into the project's current status and results that were presented at our Progress Meeting. We would also like to express special thanks to the members of our Technical Advisory Board and our Users' Group for their feedback and contributions at the meeting and beyond.

Victor Hugo Sanchez Espinoza
Coordinator

WP2 – Experimental investigations of SMR key phenomena and code validation

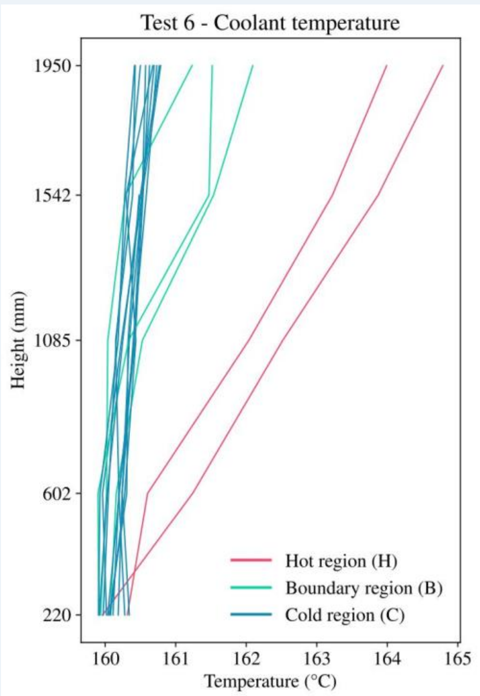
WP2 has been devoted to thermal hydraulic experiments and code validation for SMRs. Experiments are conducted by KIT with the COSMOS-H facility in Karlsruhe, Germany, by LUT with the MOTEL facility in Lappeenranta, Finland and by KTH with the HWAT facility in Stockholm, Sweden. The experiments at the three test facilities provide measurement data for the validation of thermal hydraulic analysis codes from computational fluid dynamics (CFD) to subchannel and system thermal hydraulics. Six project partners (KIT, LUT, UJV, UPM, TBL, KTH) participate in the effort validating a total of ten different thermal hydraulic tools, such as, OpenFOAM, VIPRE and TRACE, to name a few.

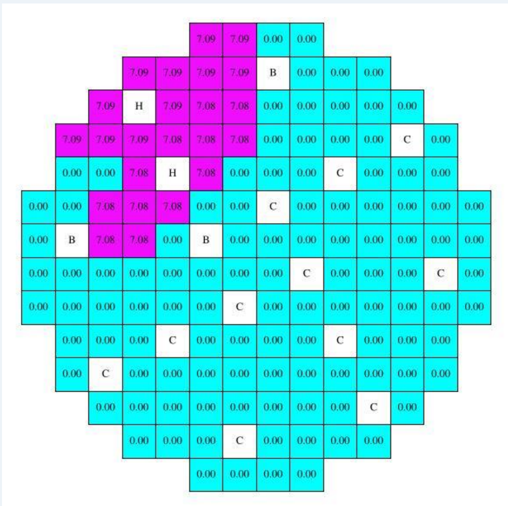
COSMOS-H is a water loop with the maximum pressure and temperature of 170 bar and 360 °C, respectively. In McSAFER, the loop is used for boiling experiments in prototypic SMR fuel geometries and conditions up to the boiling crisis. The facility features a test section of modular design with two high pressure sight glass modules that are utilized to obtain high quality data with optical measurement techniques. Inside the test section, first a single heated rod is placed, followed by a rod bundle in later experiments. The COSMOS-H facility was completed at the end of 2022 and obtained operating license in June 2023 after successful pressure and safety tests. The first COSMOS-H experiments are being carried out at the time of release of this newsletter.

COSMOS-H facility at KIT

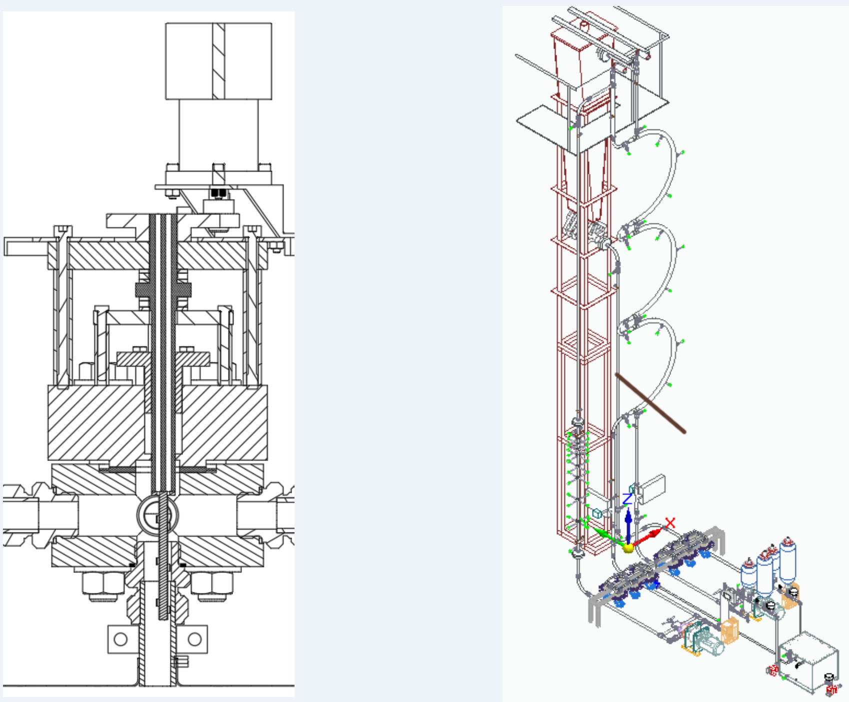
MOTEL is an integral test facility of modular design which for the McSAFER experiments represents a model of an integral PWR type SMR operating at natural circulation with the core, the helical steam generator, and the pressurizer all inside a single pressure vessel. The facility is used to investigate the behaviour of the steam generator and core cross flows. The steam generator tests investigate the stability and superheating performance at different steady heating powers up to the facility maximum of 1 MW. The core cross flow tests consider different radial power distributions as the core has a relatively large diameter with a total of 132 heater rods distributed into 12 individually controlled heating segments. The MOTEL facility became operational already in the beginning of McSAFER and all the planned experiments have been successfully completed.





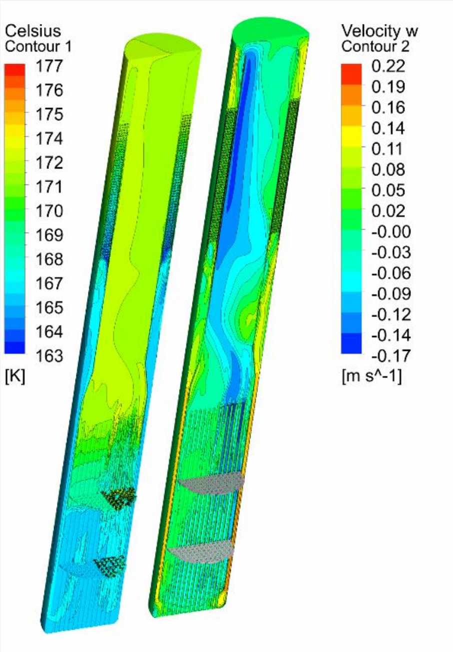
MOTEL core crossflow experiment results
(core axial temperature profile and the related radial locations of the hot, boundary and cold region temperature measurements). The core diagram shows the heater powers in kW.

HWAT is a water loop for two phase flow investigations capable of 2 kg/s flow rate, 250 bar pressure and 450 °C temperature with a maximum heating power of 1 MW. HWAT is used to investigate heat transfer up to critical heat flux, flow stability in natural circulation, power void reactivity feedback and non-linear power profile in typical SMR conditions, considering also transition from forced to natural circulation. First tests include forced circulation steady states with an electrically heated riser as the test section, while for the further experiments the facility will be modified with the inclusion of another loop via a steam generator. The primary loop then models the in-vessel circulation of an SMR. These tests focus on forced to natural circulation transients. Information about the local flow characteristics inside the test section is obtained with a specific multi-sensor probe unit. At the time of release of this newsletter, the first HWAT test series has just been completed and the facility is being modified for the remaining experiments.

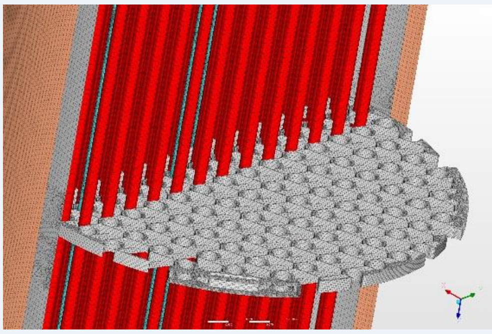


HWAT: Multi-probe unit & passive system simulator

The code validation progress follows the progress of the experiments with most of MOTEL related simulations either already finished or well underway while for the COSMOS-H and HWAT experiments simulation models have been prepared with testing and blind calculations. Highlights of the CFD code validation so far include the detailed CFD modelling of the entire MOTEL primary circuit with CFX by KIT and the porous media based CFD modelling of MOTEL with Fluent by UJV, both with good agreement with the experimental measurements. Similarly, good results have been obtained in the subchannel code simulations of the MOTEL cross flow experiments with CTF by TBL. For thermal hydraulic system codes, detailed models have been built of all the facilities and the first test simulations, e.g., by LUT with APROS and UPM with TRACE look promising.



MOTEL CFX simulations



MOTEL ANSYS CFX model

WP3 – Multiphysics Core Analysis Methodologies for SMR Applied for Safety Case Rea

Core level transient analyses have been conducted at three levels of fidelity:

1. Industry standard methods represented by nodal diffusion neutronics coupled to assembly or quarter assembly level thermal hydraulics and representative rod fuel feedback.
2. Advanced low-order methods represented by pin resolved neutronics coupled to subchannel level thermal hydraulics and rod level fuel feedback.
3. High fidelity methods utilizing Monte Carlo neutronics with detailed geometry coupled to subchannel level thermal hydraulics and rod level fuel feedback.

Modelling the same transient scenario with different levels of fidelity provides information on which safety parameters are well predicted by the industry standard methods and which safety parameters require high fidelity methods in order to be properly resolved.

It is obvious that local rod and subchannel level data such as maximum fuel temperature and minimum critical heat flux ratio can be directly predicted only by the tools with pin resolved solutions. Industry standard tools would need to apply additional approximative hot channel and hot rod analyses in order to obtain the local limiting values.

The overcooling transient for the Nuward-like F-SMR reactor was analysed with nodal diffusion (fidelity level 1) and pin level neutron transport (fidelity level 2). The maximum power reached during the transient was similar using both toolchains, but the local power peaking was clearly higher in the higher fidelity model as it could resolve the variation in power between different fuel rods in the same assembly.

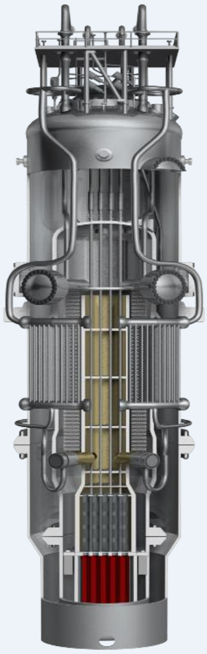
The rod ejection accident modelled for the SMART-like KSMR reactor has been modelled with nodal diffusion (fidelity level 1), pin level neutron transport (fidelity level 2) and Monte Carlo neutronics coupled to subchannel level thermal hydraulics (fidelity level 3). In the analyses, the lower the fidelity of the modelling, the higher the maximum reactor power reached in the simulation with the largest difference observed between the nodal (level 1) and pin level (level 2) solutions. On the other hand, the highest fidelity solution produced smallest margins for the local heat transfer crisis (mDNBR).

Finally, the rod ejection accident modelled for the NuScale-like reactor has been modelled with nodal diffusion (fidelity level 1) and pin level neutron transport (fidelity level 2) with the Monte Carlo (fidelity level 3) analysis still ongoing. In contrast to the KSMR transient this scenario is not prompt super critical. The reactivity insertion from the rod ejection is slightly higher with the higher fidelity model leading to the maximum power during the transient being higher with the higher fidelity model as well. The effect of the level of discretization is best seen in local data, such as maximum fuel temperatures.

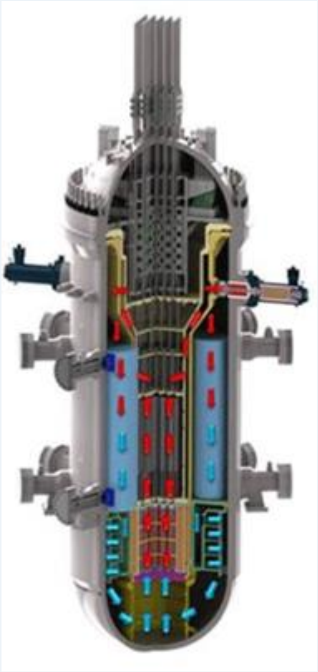
The remaining work will re-analyse the transient in the NuScale-like core using an accident tolerant fuel loading and draw conclusions on which data can be well predicted using industrial tools and which data requires pin level resolution during the transient calculation.

WP4 – Multiscale RPV Analysis Methodologies for SMR

WP4 has been devoted to RPV thermal hydraulic analysis of two SMR design NuScale (USA) and SMART (Korea). Integral concept of new SMR consider new features such as helical heat exchangers or devices added to homogenize the flow and reinforce the mixing of the coolant before entering to the core. The traditional 1D or 3D system thermal hydraulic codes often cannot catch the physics going on under nominal or accidental conditions, therefore the use of novel methods such as multiscale coupling of system-TH codes with subchannel codes and system-TH codes with CFD codes is applied to investigate the multi-dimensional and mixed convection flow inside the RPV. These multiscale methods allow better understanding and description of the thermal hydraulic phenomena inside the RPV by increasing the spatial resolution of the computational domains.



NuScale



SMART

The selected scenarios are:

- Boron dilution for NuScale reactor
- ATWS event decrease in the heat removal by the secondary system for SMART reactor

Each of the participants independently developed their own model. To provide fair comparisons between different reactor analysis toolchains and different partners of the project, a sufficiently detailed database has been prepared. As selected reactors are developed as commercial enterprises, not all required information is publicly available. From the point of view of the goals of the McSAFER project, especially regarding the comparability of results, the existence of fixed specifications is more important than the exact details of the specifications, meaning that expert judgement can well be applied in determining suitable values for missing data.

In WP4, the scope of the analyses is limited to RPV only, the calculation models include all essential components. Ex-vessel systems and components are simulated as boundary conditions BCs.

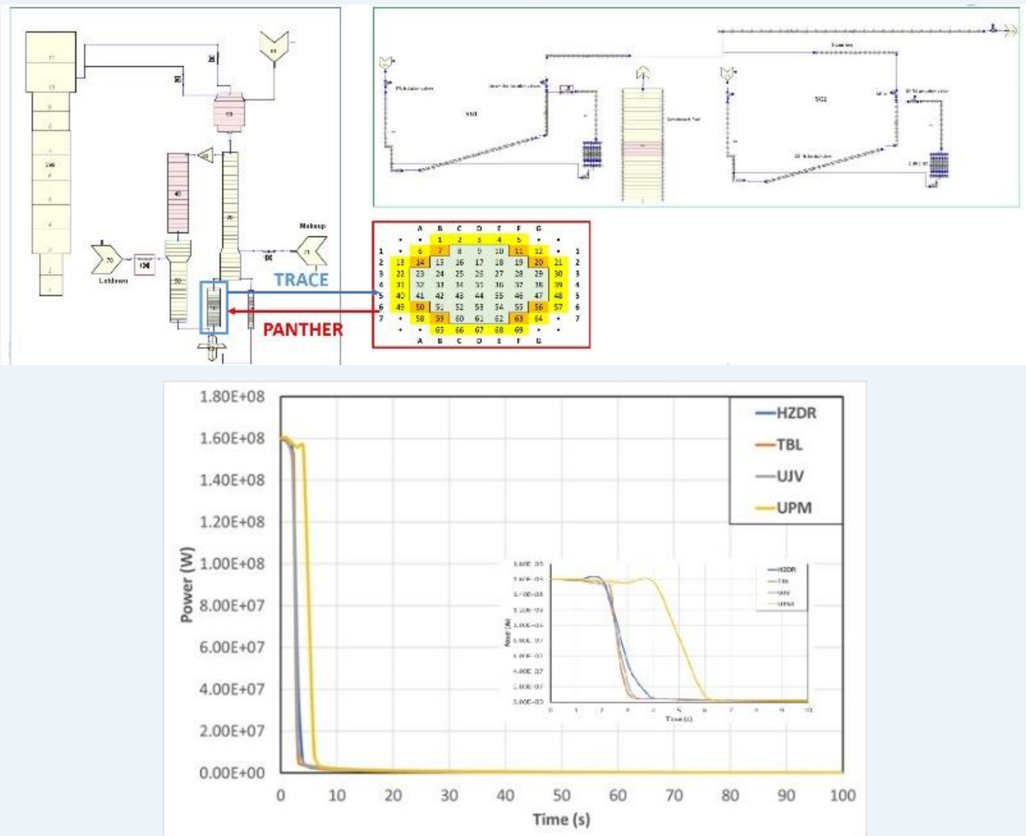
The work in WP4 is divided as follows:

- Task 4.1 - the Reactor pressure vessel (RPV) is modelled using a traditional 1D approach where each region of RPV (core, riser, downcomer, lower plenum, pressurizer) is modelled by a 1D component.
- Task 4.2 - the RPV is modelled through coarse 3D meshes, which will also allow representation of azimuthal flows.
- Task 4.3 - coupled 3D system thermal hydraulic and subchannel codes are used for detailed simulation of core behaviour.
- Task 4.4 - coupled 3D system thermal hydraulic and CFD codes are used for detailed simulation of flow mixing in the lower plenum

Task 4.1 to Task 4.3 have been successfully completed, work on Task 4.4 is currently underway. The overall evaluation and comparison of calculations will be carried out after the completion of task 4.1.

WP5 – Multi-Scale Plant Analysis Methodologies for SMR Applied to Postulated Accident Scenarios

In continuation of the WP4 work, the vessel models of the NuScale and the SMART SMR designs are extended to the whole plant. Steam line break analyses have been conducted for both SMR designs by means of thermal hydraulic system codes coupled with 3D neutron kinetic nodal diffusion codes. For the NuScale reactor, four different models have been developed by four different organizations. The figure below (top) shows the TRACE/PANTHER model of Tractebel. The bottom figure shows the power evolution obtained in the four coupled calculations. The main events are in good agreement between the code systems. On the primary side, differences are observed in the time behaviour of the core temperatures, which are triggered by the differences in the heat transfer within the steam generators.



TRACE/PANTHER coupled NuScale-model for the steam line break analyses and power evolution in the four calculations

Similar models have been developed and applied to a steamline break analysis of the SMART reactor.

In the final project phase, 3D CFD models are integrated into the downcomer models for both designs in order to adequately describe the asymmetries in coolant flow behaviour induced by the transients.

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COORDINATION
Dr. V. H. Sanchez-Espinoza (Victor.sanchez@kit.edu) · Karlsruhe Institute of Technology, Germany · Institute of Neutron Physics and Reactor Technology (INR)

CONTACT
Karlsruhe Institute of Technology (KIT) · Research Office (FOR) · email: mcsafer@for.kit.edu · www.mcsafer-h2020.eu