The H2020 McSAFER: High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic Small Modular Reactors

IAEA/McSAFER Workshop on Core and Plant Simulation with an Emphasis on Fuel Behaviour in Light Water Reactor Based Small Modular Reactors

V. H. Sanchez-Espinoza (McSAFER Coordinator)

27-29 February 2024

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945063.

Content

- Goals and scientific approach
- Work packages, partners
- Challenges, methods / tools
- Highlights
- Dissemination
- Summary

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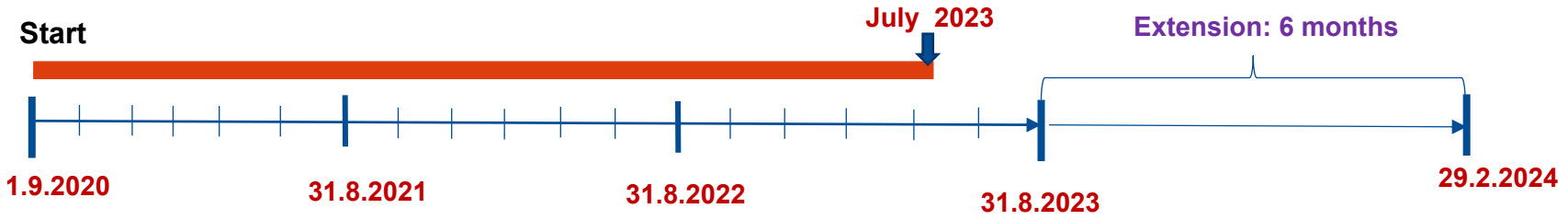
Technical Goals & Scientific approach

- Contribute to safety research for water cooled SMR
- Perform key thermal hydraulic experiments at three European facilities
- Validate thermal hydraulic tools using McSAFER data
- Develop / improve simulation tools for safety analysis of SMRs based on multi-physics / -scale
- Demonstrate advantages of multi-physics /- scale tools compared to industry-like tools

Scientific approach: Combine experimental investigations and numerical simulations

Project Timeline:



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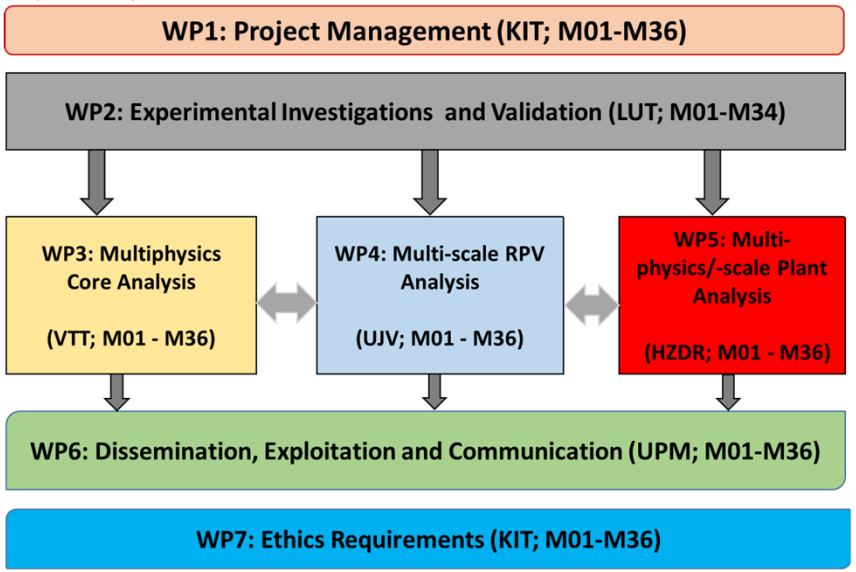
McSAFER: Work Packages, Partners



McSAFER: Work Package Structure

Universities

R&D, TSOs

Industry

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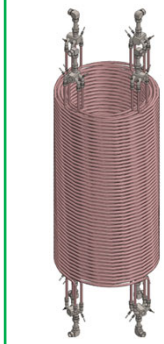
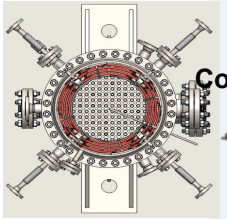
McSAFER Experimental Facilities: MOTEL, COSMOS-H, HWAT

LUT

PZR

Helical coil HX

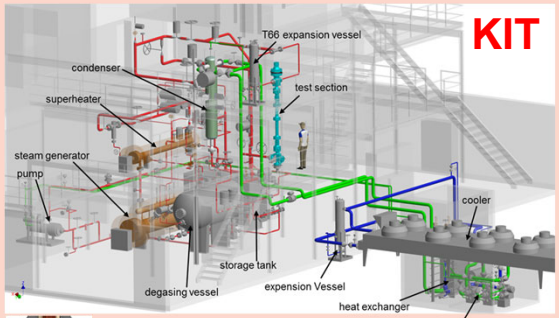


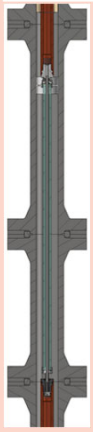


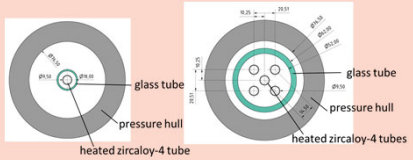
Core

MOTEL Nat. Circ. Loop

KIT



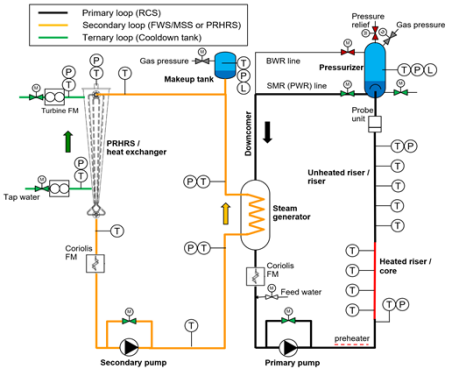




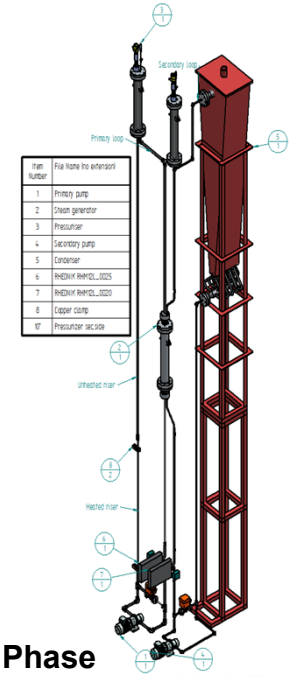
Serie-1 Serie-2

COSMOS-H: Test Section

KTH



High-P, High-T Loop for two Phase Flow Investigations (SS/TR)



HWAT Test Section

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McSAFER Experimental Facilities: Key Parameters, Features

Key-Parameters	COSMOS-H	MOTEL	HWAT
Focus	Fundametal HT, Boiling, CHF	HX-performance, core crossflow	forced convection SS, transition to natural circulation, natural circulation
Power (MW)	2 (0.6)	0.99	1
Pressure (MPa)	5 to 17	4 MPa (PS) / 4 MPa (SS)	25
Max T_inlet (°C)	370	250 (PS) / 250 (SS)	450
Mass flow rate (kg/s)	0-1.4		1.5
Loop height (m)/D (m)	3.54 /0.08	7.4 / 0.711	8.8
Test section:			
Height (m)	1 to 2	1.830	3.7 (heated riser), 1.89 m diff between hot/cold sections
Heated rods /tubes	1 tube, 5 tubes	132 (heated) / 145 (dummy)	1
Instrumented rods	all	16	
Instrumentation:	Many TCs, p-sensors, high-speed cameras and LDA	340 TCs, 212 in the core, 5 p-sensors, 7 diff. pressure, Ultrasonic flowmeter	Multi-sensor probe at exit if heated riser to measure velocity, void and temperature, DP-transducers, Coriolis flow meter, TCs

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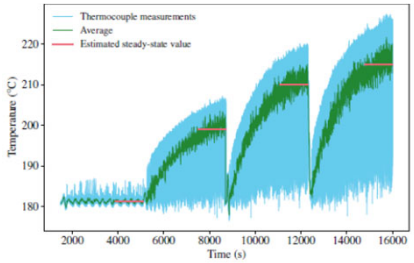
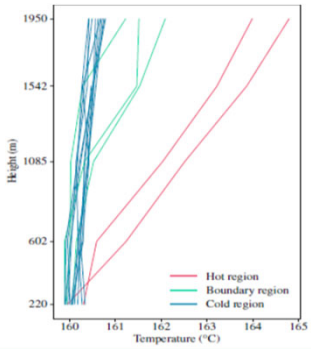
Highlights: Experimental Investigations

MOTEL Facility:

- Serie 1: Helical HX performance (~10 tests)



- Serie 2: Cross flow in core (x tests)



HWAT Facility:

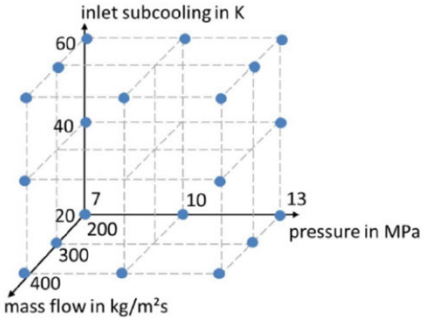
- 40 test done NC, FC, N2F
- 9 tests selected for code vaidation

#	Test type	Test date [YYMMDD]	Pressure range [bar]	Flow rate range [kg/s]	Flow rate flux range [kg/sm²]	Power range [kW]	Power flux range [kW/m²]	Comments	Optical probe used
20	Forced	230620	5-78	0-0.8	0-2901	0-177	0-812		No
23	Forced	230808	9-102	0-0.21	0-752	3-278	-13-1270		No
32	Forced	230810	29-81	0-0.93	0-3311	37-353	169-1616	Data from TC #1, 17 excluded due to poor quality.	No
34	Forced	230815	101-123	0.05-1.46	183-5204	43-154	197-704	Data from TC #1, 2, 14, 19 excluded due to poor quality.	No
36	Natural	230616	59-79	0-0.12	0-439	0-120	0-548		No
37	Natural	230630	10-75	0-0.11	0-387	0-134	0-614		Yes, runs 30, 31, 32, 33
38	Natural	230807	51-94	0.02-0.16	84-577	0-238	0-1091	Data from TC #5, 10, 11, 23 excluded due to poor quality.	No
43	F2N	230811	67-93	0.05-1.43	181-5097	116-125	533-570	Data from TC #1, 2, 17, excluded due to poor quality.	No
44	F2N	230815	119-141	0.05-1.44	183-5143	117-125	534-573	Data from TC #1, 2, 14, 19 excluded due to poor quality.	No

- Test series 2: in March 2024

COSMOS-H Facility: HT convention to DNB

- Serie 1: one single heated Zry-tube (20 tests)
  - In March 2024
- Test series 2: five heated Zry-tubes
  - ?



Parameter matrix for DNB tests

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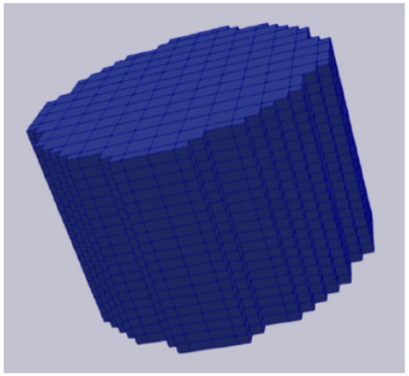
Validation of Thermal Hydraulic Codes using McSAFER-Data

Remarks:

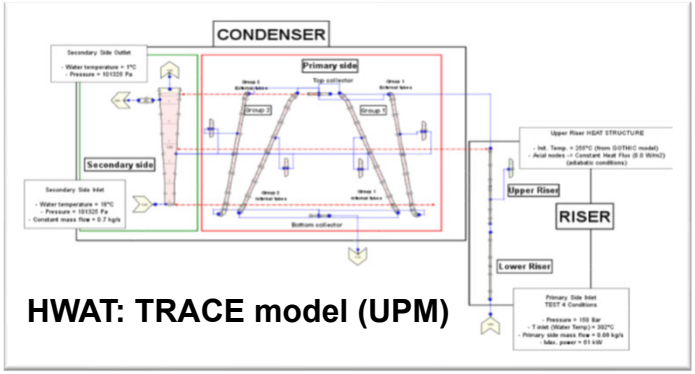
- Different thermal hydraulic codes: CFD, Subchannel and system TH codes
- Different partners involved with different tools

Tests	CFD	Subchannel	System TH
COSMOS-H	KIT LUT UJV	KIT UJV	KIT UJV
MOTEL	KIT UJV	TBL UJV	LUT UPM
HWAT	KTH		KTH UPM

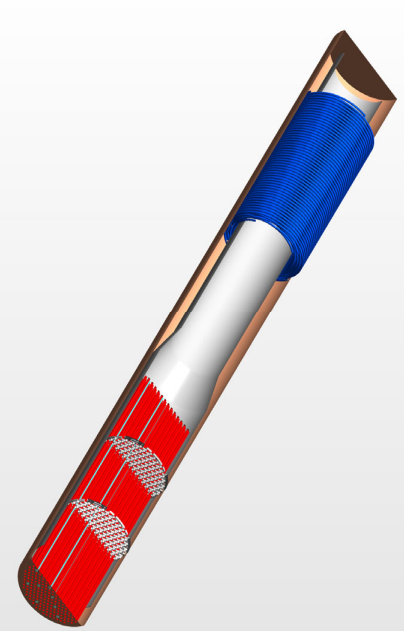
McSAFER Validation Matrix



MOTEL: CTF Core Model (TBL)



HWAT: TRACE model (UPM)



MOTEL: CFD (CFX) Model of the facility (KIT)

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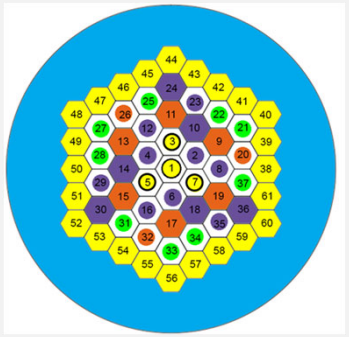
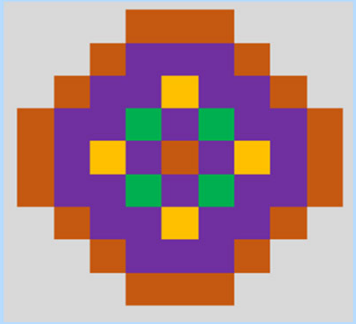
WP3: Multi-physics Core Analysis of different SMR-Cores



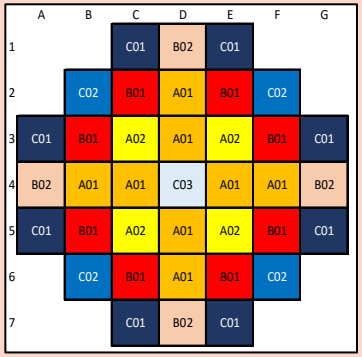
CAREM-Like core

- 61 HEX FA (1.4 m)
- Some FA with BP (6-12)
- 25 control FA
- U-235 enrichment: 1.8 to 3.1 %



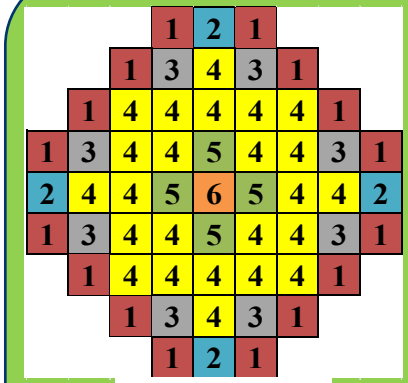
FSMR Core

- 57 FA 17x17-24-1 (1.6 m)
- All FA with AIC-rods
- Gd-rods (6-10 %)
- Heterogeneous FA-design
- Different enrich.3.5-4.95 %



NuSCALE-Like core

- 37 FA 17x17-24-1 (2m)
- GD-rods (16)
- U235 enrich: 1.5 -4.55 %
- Control rods design: Axial varying CR-materials: AIC, B4C



KSMR Core

- 57 FA 17x17-24-1 (2 m)
- 6 FA designs, each with CRs (AIC, B4C, SS)
- U235 enrich: radial/axial (2-4%)
- 20-24 BP rods (B4C, Al_2O_3)

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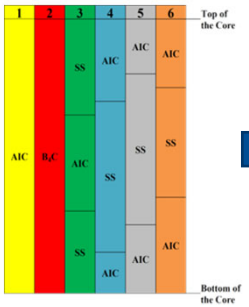
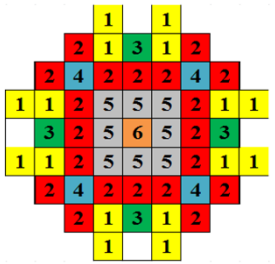
WP3: Challenges of Water-cooled SMRs for Core Physics

- Compactness
- High leakage
- Small size (H and D)
- Heterogeneity (radial, axial) of FAs
- Harder spectrum
- Complex control rod designs
  - Different types and materials
  - Axial heterogeneity
- Increased role of reflector



KSMR: different Control rod types



KSMR Core: Radial location of the CR-types

McSAFER Approach

- Nodal diffusion /1D TH or Subchannel
- Pin-based transport / Subchannel
- Pin-based MC /Subchannel (SS, Transiet)

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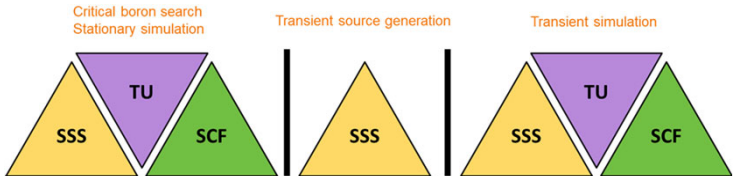
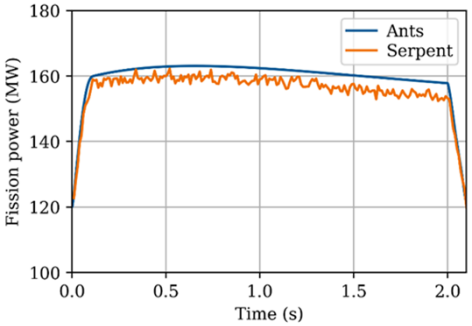
WP3: Highlights of high-fidelity SMR Core Analysis

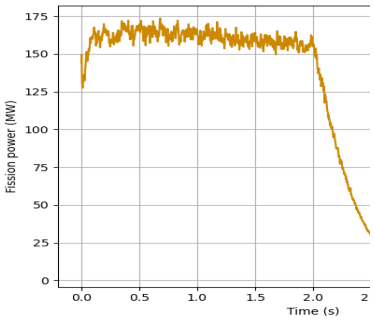
- **NuScale: REA Analysis**



SSS-SCF-TU: three-step simulation approach

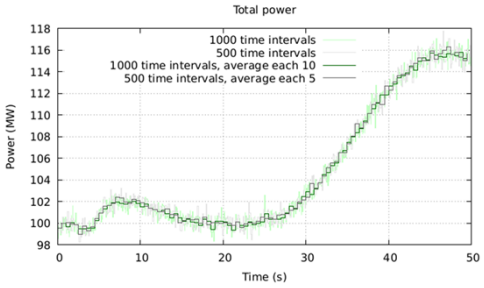


NuScale REA: ANTS/SCF vs SSS2/SCF

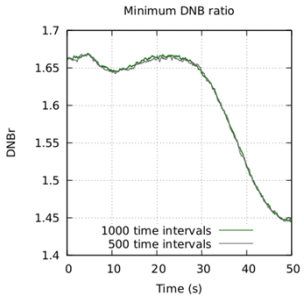


NuScale REA: SSS2/SCF/TU

- **CAREM Cold Water Transient Analysis**



CAREM: Power evolution



CAREM: Predicted DNBR

First-of-the-kind results:

- **REA with MC/subCh/TM**
- **long transients with MC/subCh**

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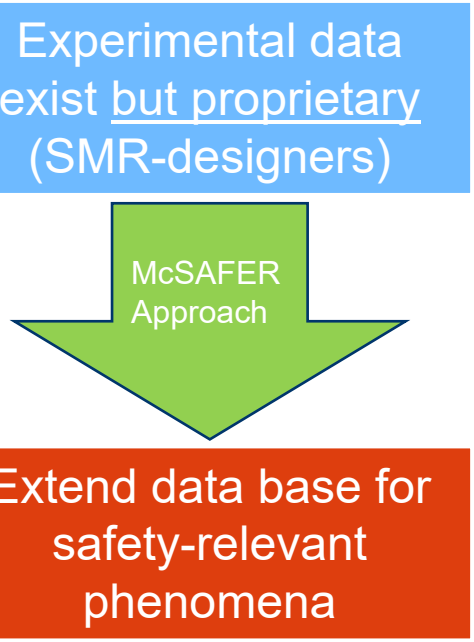
WP4/5: Challenges of int. SMR for Thermal Hydraulics & Safety

- Integrated water-cooled SMR
  - Many components inside RPV like pumps, helical HX, etc.
  - Hence, 3D perturbed flow inside RPV
  - Core thermal hydraulics:
    - cross flow, DNB similar to the one of large PWR cores?
  - Cores with natural circulation (CAREM, NuScale)
    - Stability of natural convection flow
  - Cores with forced convection
    - Transition from forced to natural convection
  - SMRs equipped with PRHRSs
    - Effectiveness to remove decay heat



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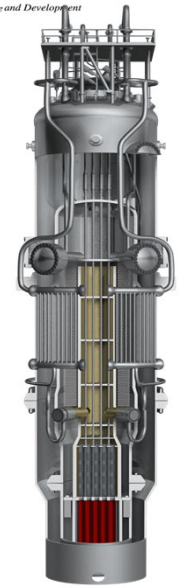
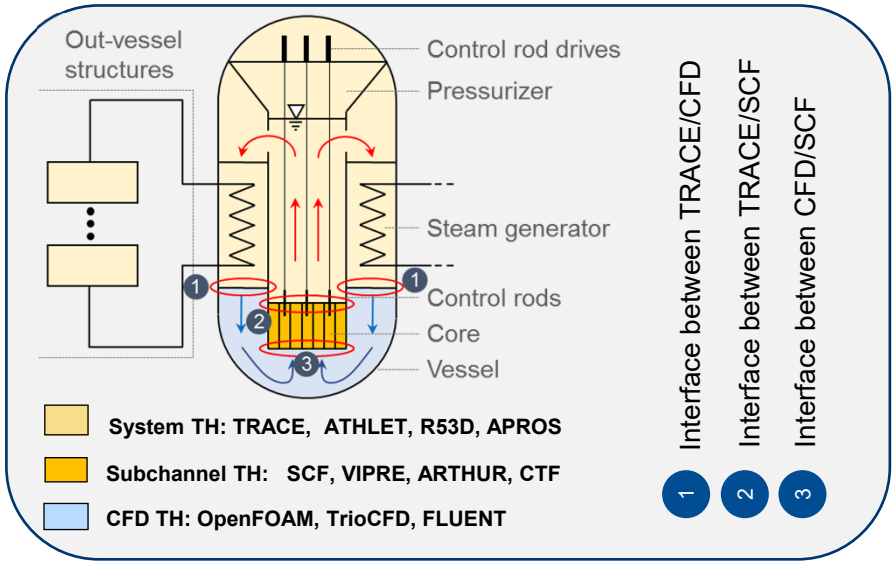
WP4/5: Multiscale Methodologies for SMR RPV / Plant



NuScale (USA)

WP4: Boron dilution

WP5: SLB

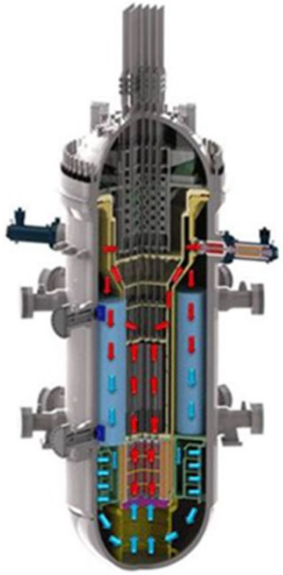


WP4: Multiscale coupling

- System TH/ Suchannel TH
- System TH/ CFD

WP5: Multi-scale /-physics coupling

- System TH/ Suchannel TH/3D NK
- System TH/ CFD / 3D NK



SMART (South Korea)

WP4: ATWS

WP5: SLB

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WP4: Multi-scale Methods for Transient Analysis of SMR

SMART ATWS

Partners: KIT, TBL

- 1D/3D TH analysis: TRACE, RELAP, etc.
- System TH/Subchannel:
  - TRACE/SCF/ICoCo (KIT)
- System TH/CFD:
  - TRACE/OpenFOAM/ICoCo (KIT)

NuScale Boron Dilution

Partners: HZDR, UJV, UPM, JACOBS, TBL, JRC

- 1D /3D TH analysis: TRACE, RELAP3D
- System TH/Subchannel:
  - TRACE/SCF/ICoCo (UPM)
  - TRACE/ARTHUR (JACOBS)
- System TH/CFD:
  - ATHLET/FLUENT (UJV)
  - ATHLET/TrioCFD (HZDR)

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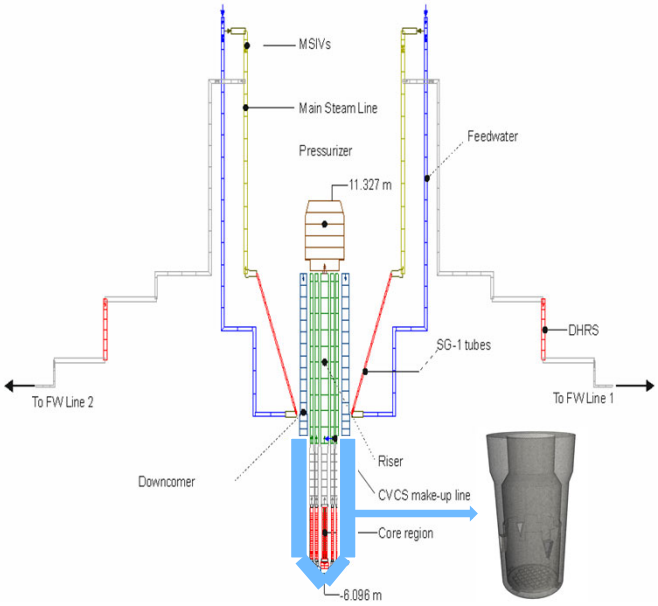
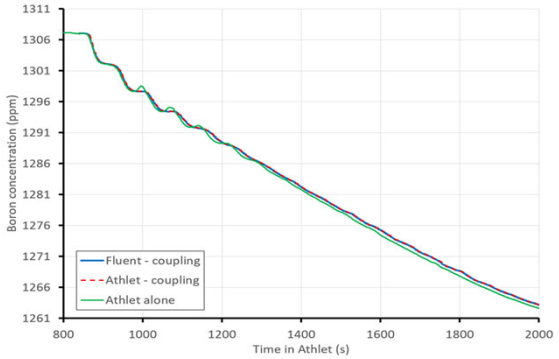
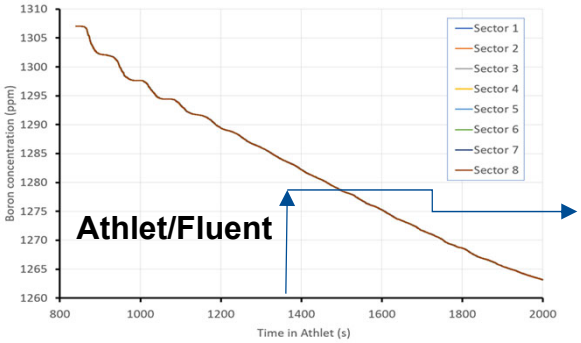
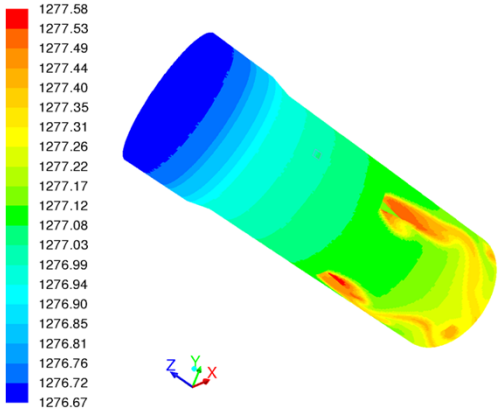
WP4: Highlight: Multiscale Analysis of NuScale Boron Dilution

- **Boron dilution transient:**
  - **HZDR: ATHLET/TrioCFD**
  - **UJV: ATHLET/FLUENT**









Athlet/Fluent: Boron concentration in downcomer in Fluent, time 1539 s

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WP5: Multi-physics/-scale Methods for Plant Analysis

SMART Steam Line Break (SLB)

Partners: KIT, TBL

- 1D TH /3D Neutronics (N):
  - TRACE/**PANTHER** (TBL)
  - TRACE/**PARCS** (KIT)
- System TH/ SubCh/ **3D N**:
  - TRACE/**PARCS**/SCF/ICoCo (KIT)
- System TH/ **3D N** /CFD:
  - TRACE / **PARCS** / OpenFOAM / ICoCo (KIT)

NuScale Steam Line Break (SLB)

Partners: HZDR, UJV, UPM, JACOBS, TBL

- 1D TH/ **3D Neutronics**:
  - ATHLET/DYN3D (HZDR)
  - TRACE/PANTHER (TBL)
  - ATHLET/DYN3D (UJV)
  - TRACE/PARCS (UPM)
- **System TH/ 3D N/ SubCh:**
  - TRACE/PARCS/SCF/ICoCo (UPM)
  - TRACE/WIMS/ARTHUR (JACOBS)
  - TRACE/PANTHER/CTF4 (TBL)
- **System TH/ 3D N/ CFD:**
  - ATHLET/DYN3D/FLUENT (UJV)
  - ATHLET/DYN3D/TrioCFD (HZDR)
  - TRACE/ANTS/OpenFOAM (VTT)

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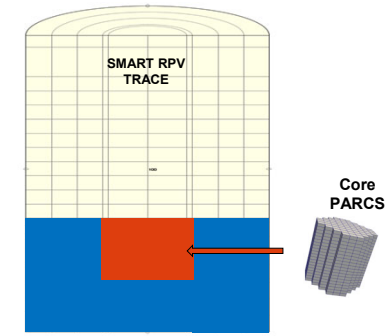
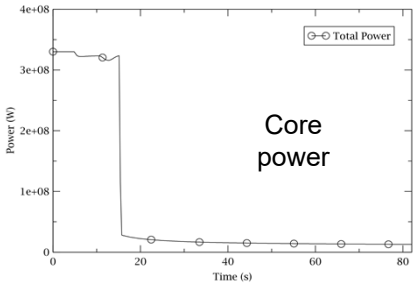
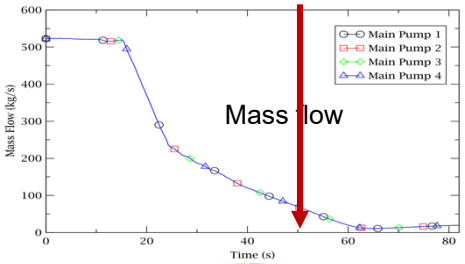
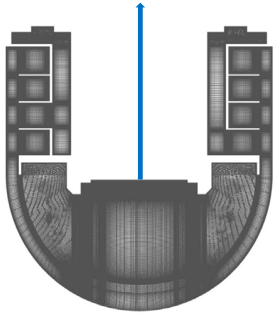
WP5: Highlights of Multiscale Analysis SMART SLB

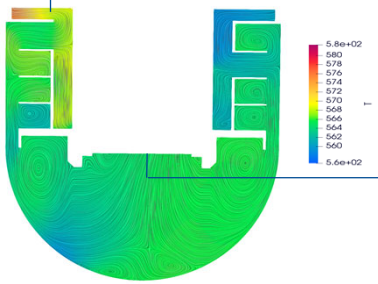






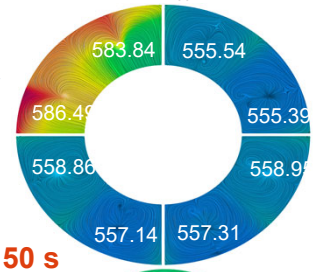


OpenFOAM Meshing



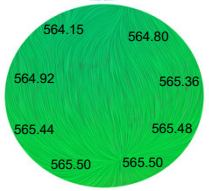
openFOAM
Results

Plane: Below HX

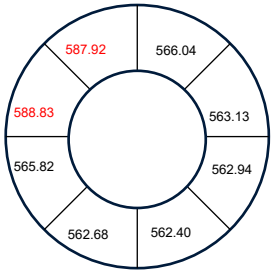


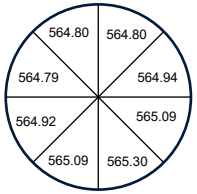
Transient time: 50 s

Plane: Core entrance



OpenFOAM





TRACE

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945063.

McSAFER: Dissemination of Main Results

McSAFER Zenodo Open Repository:

https://zenodo.org/communities/mcsafer/

User group members:
NRG, IRSN, ININ, BME, FRAMATOME GmbH

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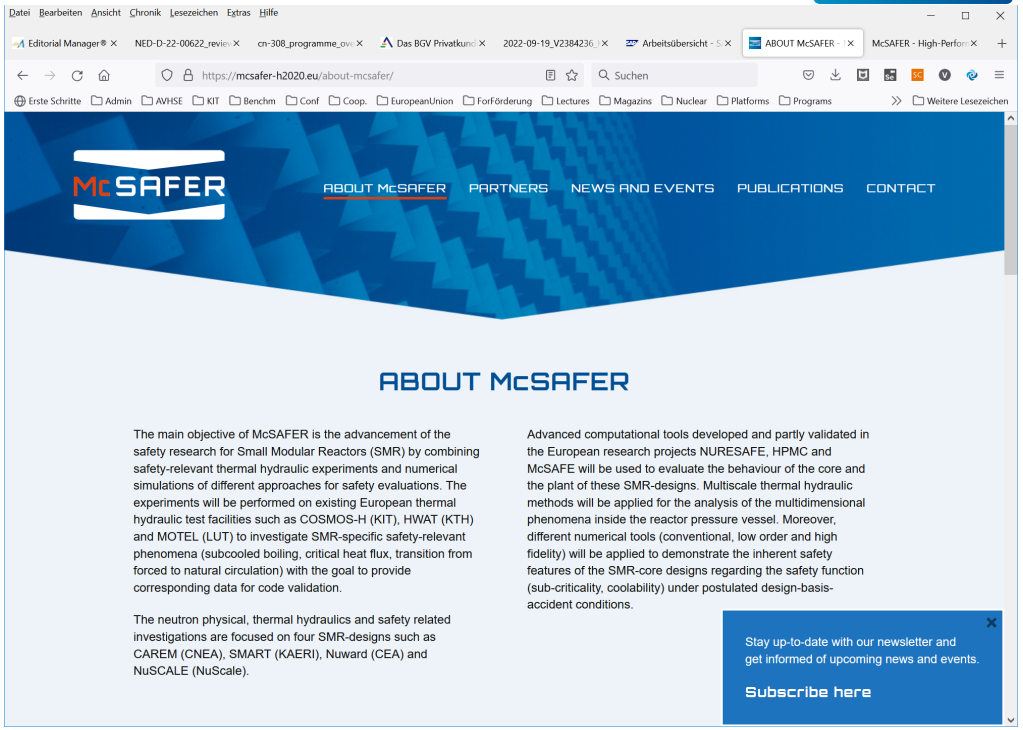

Visit public website: www.mcsafer-h2020.eu

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Summary

- Experimental program provide key-data for code validation regarding
  - Performance of helical coil HX
  - Cross flow in the core
  - DNB, transition from forced to natural circulation

- Analysis of core transients with different approaches emphasizes the **need of advanced tools** (transport, MC, subchannels) to assess complex, small, heterogeneous SMR-cores

- Safety evaluations of SMR-transients with different "**simulation tools**" contributes to identify most appropriate **tools** for SMR-plant behavior
  - Reduce conservatism
  - Enhance operational flexibility
  - Improve economics

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Acknowledgements

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McSAFER Workshop Survey: Questionnaire

- **Online option:** Visit the link online survey and be so kind to answer the questions: (anonymous and in line with GDPR regulations)
  - Collect feedback from the participants (different stakeholders) for internal use in the McSAFER Deliverable (D6.11)
  - You feedback will be evaluate for the McSAFER impact

- **Printed Option:** Questionnaire to be distributed among the participants
  - It will be collected the last day of the Workshop

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