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

20. IAEA TWG FPT Meeting (EVT2105273)

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

Content

- Goals and scientific approach
- Partners, budget
- Work packages
- Selected SMR-designs
- Challenges and solution approach
- Education & Training, Dissemination

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Technical Goals & scientific approach

Technical goals:

- Advance the safety research for water cooled SMR
  - Perform key experiments relevant for SMR-safety (core, helical HX) at EU-facilities (COSMOS-H, MOTEL, HWAT)
  - Develop, improve, validate simulation tools for safety evaluations of SMRs
  - Demonstrate advantages of advanced (multiphysics /multiscale) tools compared to legacy ones
- Apply simulation tools to four SMR-designs (F-SMR, CAREM, NuScale, SMART)

Scientific approach:

- Combine experimental investigations with numerical tools for safety
- Consider different SMR-designs:
  - Natural circulation: CAREM, NuScale
  - Forced convection: F-SMR, SMART
  - Core design: square (F-SMR, SMART, NuScale) and hexagonal (CAREM) fuel assemblies
  - Etc.

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Partners and Budget

Partners: 13

- R&D: CEA, VTT, HZDR, UJV, JRC KA, CNEA
- **Universities:** LUT, UPM, KIT, KTH
- **Industry:** Jacobs, TRACTEBEL, PEL

Budget:

- Total: 4 045 133.75 €
- EC-contribution: 95 %

  (3 995 982.50 €)
- In-Kind: 5 %

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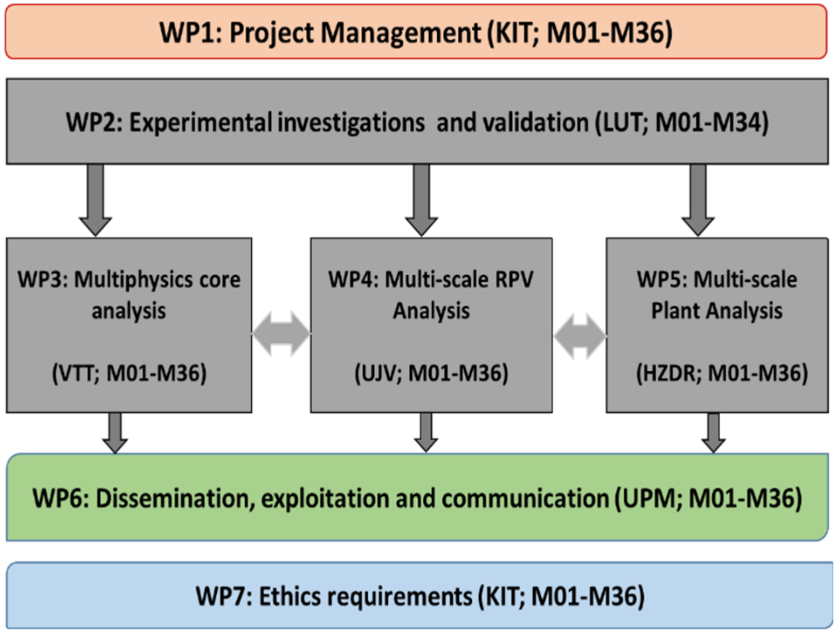
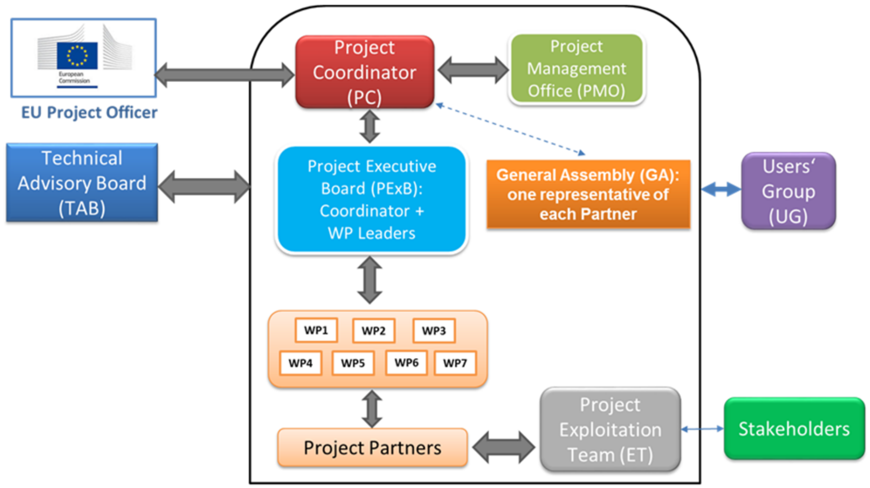
McSAFER: Work Packages, Interactions



McSAFER: Work Package Structure



McSAFER: Management Structure

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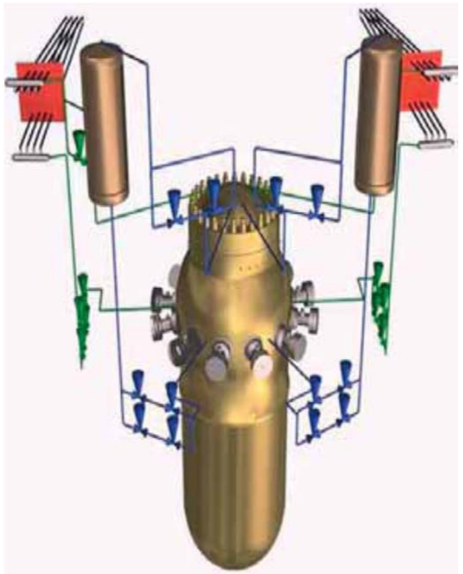
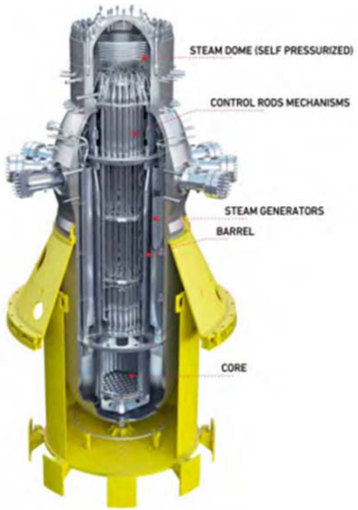
SMR-Designs under investigations: CAREM



RPV and Secondary Side

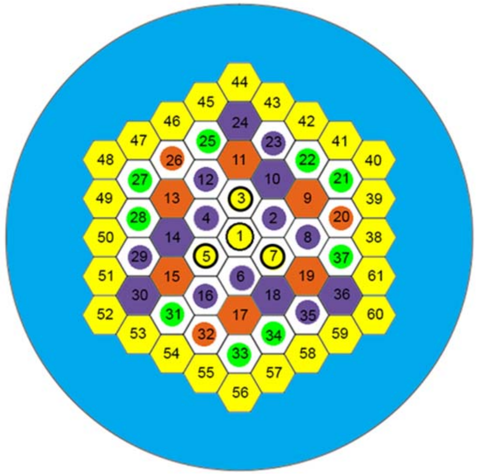
IAEA-2012: Status of Small and Medium sized Reactor Designs. A supplement to the IAEA Advanced Reactor Information System (ARIS)



RPV and Internals

Ch. Marcel; CAREM-25: A safetr innovative Small Nuclear Power Plant. Nuclear Revista Espanha 1, Enero 2017.

- 61 FA @163 pins (1.4 m)
- Some FA with BP (6-12)
- 25 control FA
- U-235 enrichment: 1.8 to 3.1 %



CAREM-Like core

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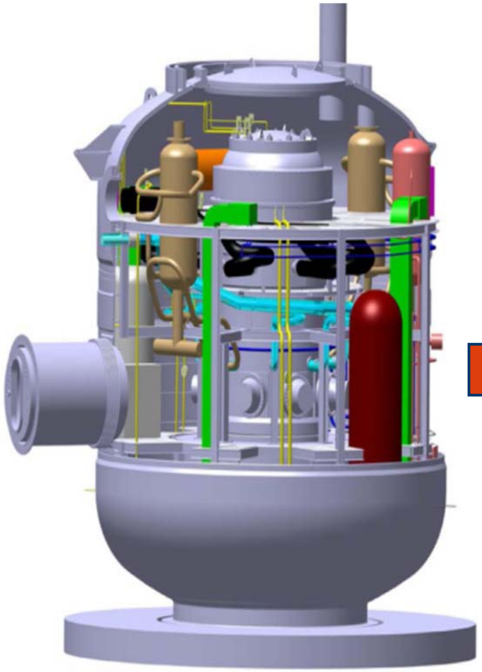
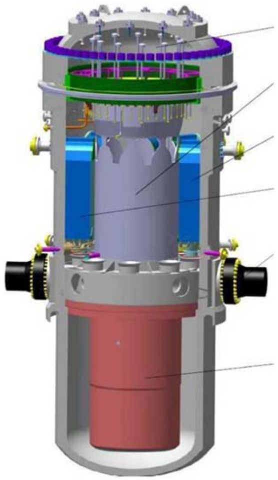
SMR-Designs under investigations: FSMR

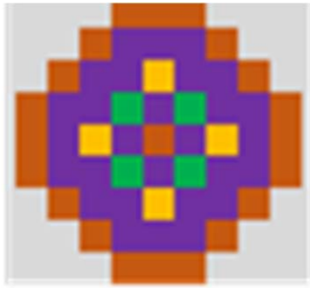
- 57 standard FA 17x17-24-1
- All FA with control rods (AIC)
- Gd-rods (6-10 %)
- Active height: 1.6 m
- 4 FA designs (heterogeneous)
- U225 enrichment: 5 zones (3.5-4.95 %)



RPV and Secondary Side



RPV and Internals



FSMR Core

J. Chenais, M. Brun; SMR/The French Approach. IAE SMR Technical working group meeting. Vienna, July 8-11. 2019

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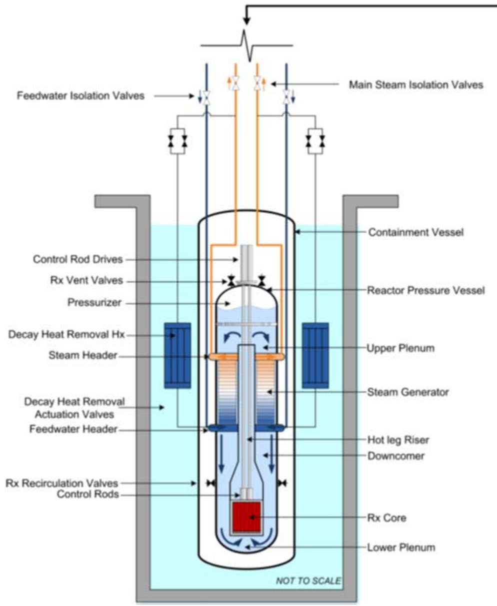
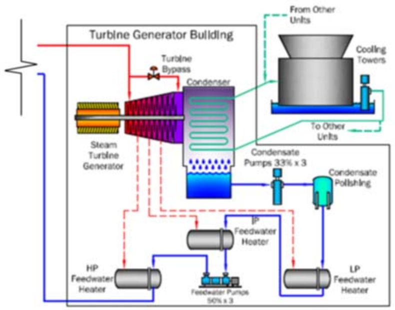
SMR-Designs under Investigation: NuScale





Integral Plant

NuScale Plant Design Overview Revision 2. NP-ER-0000-1198-NP. September 16 2013. NuScale Power LLC.

RPV and Internals

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

	A	B	C	D	E	F	G
1			C01	B02	C01		
2		C02	B01	A01	B01	C02	
3	C01	B01	A02	A01	A02	B01	C01
4	B02	A01	A01	C03	A01	A01	B02
5	C01	B01	A02	A01	A02	B01	C01
6		C02	B01	A01	B01	C02	
7			C01	B02	C01		

Core

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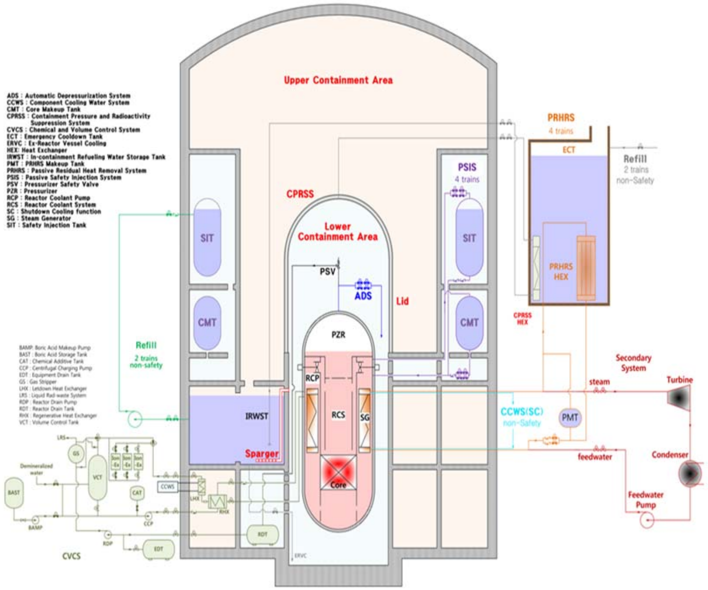
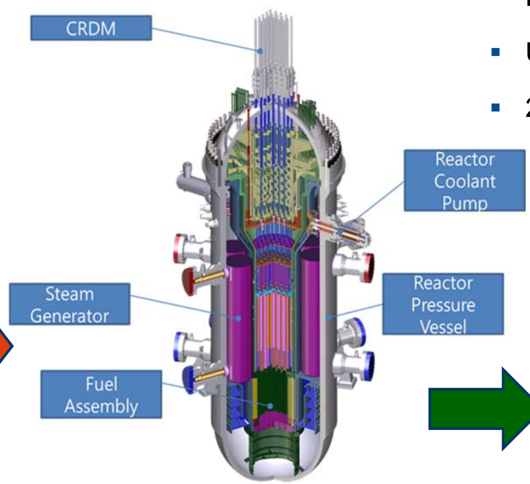
SMR-Designs under Investigation: SMART

- 57 FA 17x17-24-1 (active height:2 m)
- 6 FA designs,
- Each FA with CRs (AIC, B4C, SS)
- U245 enrich: radial/axial (2-4%)
- 20-24 BP rods (B4C, Al_2O_3)

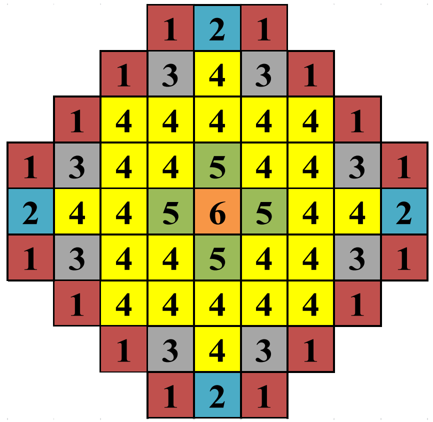


Integral Plant



From: http://smart.kaeri.re.kr/pages/view/20/cooper

RPV and Internals



KIT KSMOR-Core

Source: BAE, KYOO HWAN "*Safety Analysis for the Major DBAs in Passive PWR SMART*", 28-29 June 2018

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Challenges I: Safety relevant TH Phenomena

- Experimental data exist but proprietary (SMR developers)
- Public SMR-specific data for research community needed e.g.
  - Cross flow in the core
  - Helical HX
  - Transition from
    - Forced to natural convection
    - Natural to forced convection
  - Safety parameters like
    - CHF
  - 3D flow inside the RPV
  - Effectiveness of PRHRS
  - Stability of natural convection flow
- Data need for code validation

McSAFER Solution Approach:

- COSMOS-H experimental program:
  - Fundamental HT, boiling, CHF
- HWAT experimental program`:
  - System behavior under natural circulation
  - Transition to forced convection
  - Transition to natural convection
- MOTEL experimental program:
  - Helical HX heat transfer, pressure drop
  - Cross flow in the core

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WP2: Key Experimental Investigations & Validation

- **Fundamental heat transfer tests for SMR at KIT COSMOS-H facility**
  - Investigation of boiling under forced convection up to CHF in rod geometries

- **SMR thermal hydraulic experiments at LUT MOTEL facility**
  - Representing iPWR SMR operating with natural circulation and equipped with a helical steam generator

- **Tests at the KTH HWAT facility for SMR**
  - Forced/natural circulation test, investigation of heat transfer including CHF in condition relevant for SMRs

COSMOS-H test Facility (KIT)

MOTEL Facility (LUT)

HWAT Multisensor Probe Unit (KTH)

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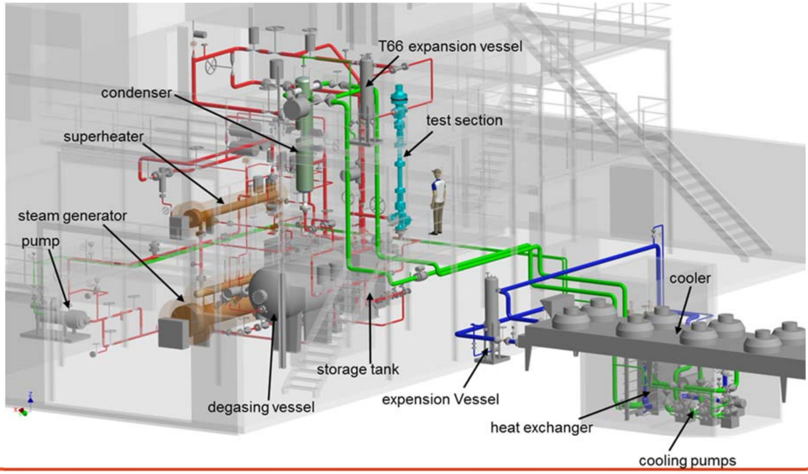
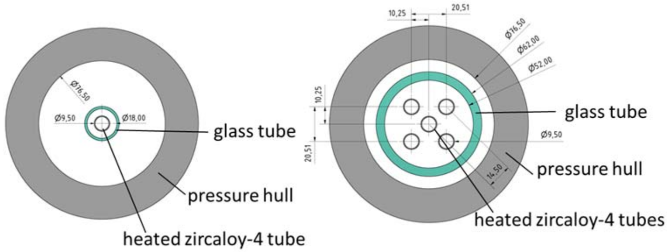
COSMOS-H Facility (KIT): Experiments and Status

- Two test series: **single rod**, **5 rod bundle**
- Test matrices defined based on review of various SMRs
- Stepwise power increase up to CHF
- Optical access (LDA, high-speed camera)
- **Facility commissioning and first tests approaching**



Parameter	Value
Working fluid	Demineralized water
Max system pressure / temperature test loop	17 MPa @ 370°C
Range of mass flow rate	0.5 – 10 m³/h
Thermal power facility	~ 2 MW
Thermal power for test section	600 kW DC
Required time for load shedding	0.15 s
Heated length	1 m

Key data of the test facility



Cross-sectional view of the two planned test arrangements

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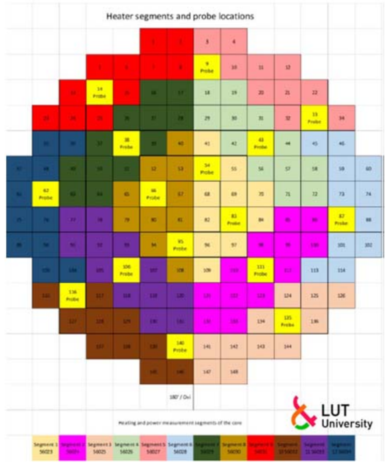
MOTEL Test Facility (LUT): Experiments and Status

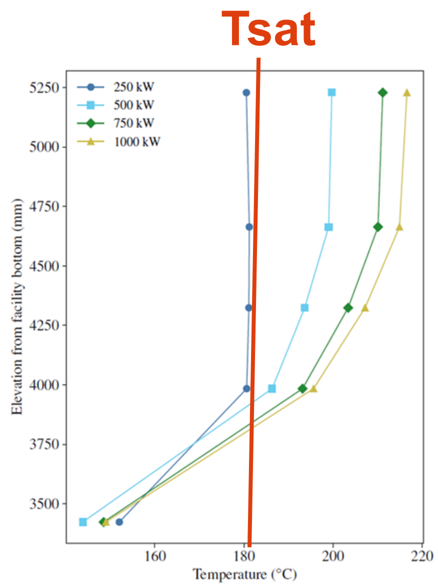
- Two test series: **SG performance**, **core cross flow**
- SG tests completed, total of 8 steady state steps
- Core cross flow tests with uneven radial power distributions under planning

CHARACTERISTICS	MOTEL
Total height [m]	7.4
Outside diameter of main vessel [mm]	711
Maximum primary/secondary pressure [bar]	40
Maximum primary/secondary temperature [°C]	250
Number of helical coil steam generator tubes	16
Maximum core heating power [kW]	990
Number of heater rods	132
Heated length of heater rods [mm]	1830
Diameter of heater and measurement rods [mm]	19.05

CHARACTERISTICS	HELICAL COIL STEAM GENERATOR
Number of tubes / tube bundles	16 / 4
Tube outer diameter / wall thickness [mm]	15 / 1.0
Tube lengths [m]	20.0 / 21.7 / 23.4 / 25.1
Helical coil loop diameters [mm]	515 / 560 / 605 / 650
Total heat transfer area [m^2]	17.0



MOTEL Core: Heater Segments



Averaged axial temperature profiles of all steam generator tubes with different core power levels

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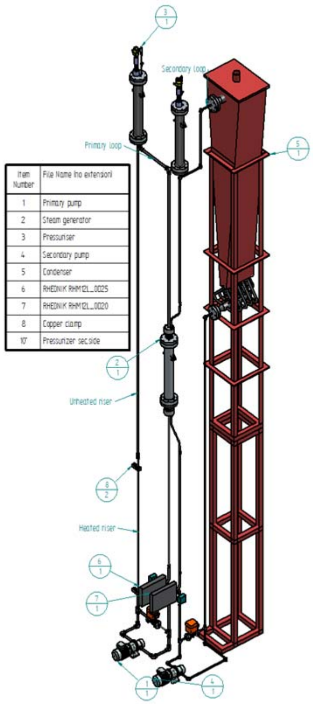
HWAT Test Facility (KTH): Experiments and Status

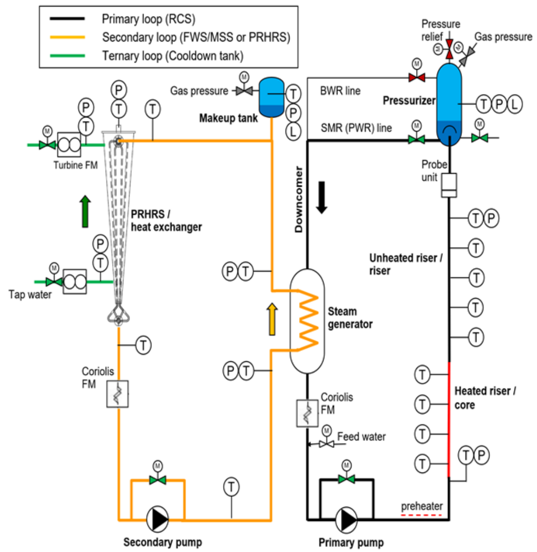


HWAT Test Loop

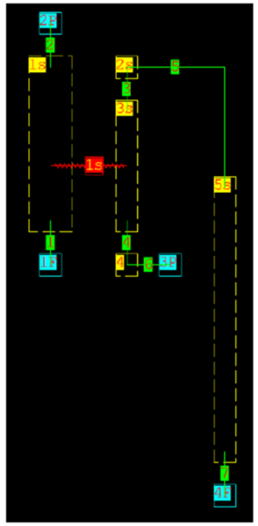
- Two test series:
  - forced circulation steady state,
  - transition from forced to natural circulation transients
- Movable multi-sensor probe equipped with optical void fraction sensor and local velocity sensor
- **First test series being completed, planning for series 2 initiated**

Parameter	Value
Maximal power, MWth	1
Maximal mass flow rate, Kg/s	1
Maximal pressure, MPa	25
Maximal coolant temp, °C	350
Effective loop height, m	8.8

Key Test Parameters



HWAT experimental setup for transient tests under natural circulation



HWAT: GOTHIC Representation (Pre- und post-test analysis)

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Validation of Thermal Hydraulic Codes using McSAFER-Data

- CFD-Codes
  - ANSYS CFX (KIT)
  - OpenFOAM (LUT)
  - FLUENT (UJV)
- Subchannel Codes
  - Subchanflow (KIT)
  - VIPRE (UJV)
  - COBRA-TF (TRACTEBEL)
- System Thermal hydraulic Codes
  - TRACE (KIT, UPM, KTH)
  - APROS (LUT)
  - RELAP5-3D (UJV)
  - GOTHIC (KTH)

- McSAFER Experimental facilities:

COSMOS-H (KIT)

Codes	COSMOS-H		
	KIT	LUT	UJV
CFD	CFX	OpenFOAM	CFX
SubCH	SCF		VIPRE
SysTH	TRACE		RELAP3D

MOTEL (LUT)

Codes	MOTEL				
	KIT	LUT	UJV	UPM	TBL
CFD	CFX		FLUENT		
SubCH			VIPRE		COBRA-TF
SysTH		APROS		TRACE	

HWAT (KTH)

Codes	HWAT	
	KTH	UPM
CFD	OpenFOAM	
SubCH		
SysTH	GOTHIC/TRACE	TRACE

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Challenges II: Core Physics

- Small size (H, D), heterogeneity
- Harder spectrum
- Increased role of reflector design
- Increased leakage from core
- Boron free cores:
  - Need innovative control rod design
  - Optimized shutdown reactivity
  - Reduced reactivity swing over the cycle
  - Etc.
- ➔ Innovations needed to improve economics and keep high safety

McSAFER Solution Approach:

- Industrial use:
  - Point Kinetics + 3D nodal diffusion e.g. ANTS/SCF, PANTHER/TRACE, SIMULATE/S3K, PUMA/SCF, DYN3D/ATHLET
- Advanced research tools:
  - Transport deterministic solvers e.g. **PARCS-SP3/SCF, APOLLO3/FLICA WIMS/ARTHUR, DYN3D-SP3/SCF**
- High-fidelity MC-based tools
  - Coupled MC / subchannel codes e.g. **Serpent2/SCF**

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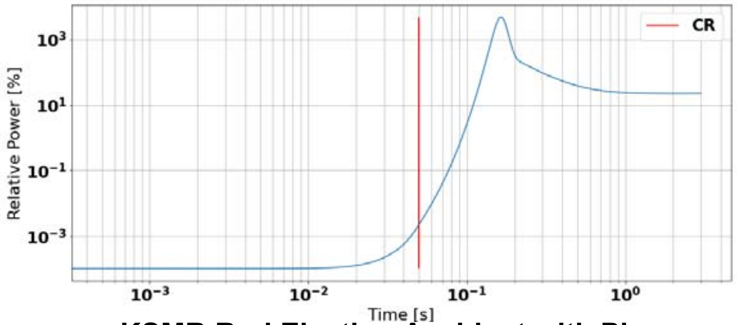
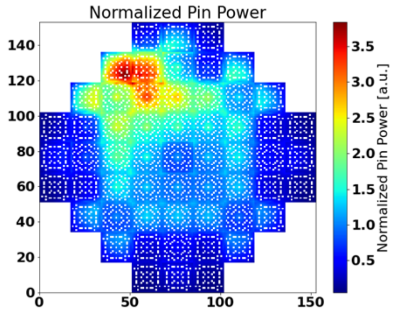
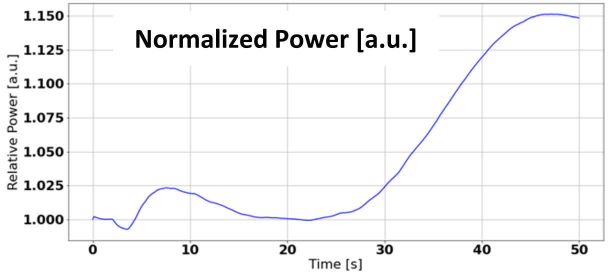
KSMR and CAREM Transient Analysis with PARCS/SCF

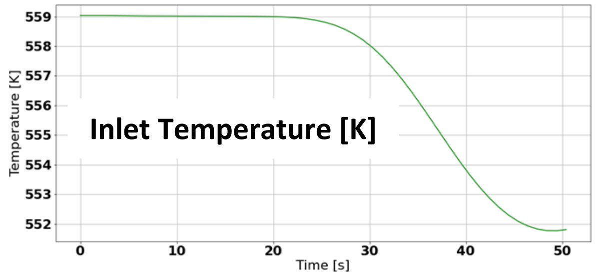


KSMR Rod Ejection Accident with Pin Power Reconstruction at power peak



KSMR REA: Relative power evolution [%]





CAREM Cold Water Transient: Power and core inlet temperature evolution

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Challenges III: 3D Thermal hydraulic phenomena in RPV

Challenges:

- Many components located inside the RPV
  - Pumps: e.g. SMART (8)
  - Helical HX e.g. SMART(8), CAREM (12)
  - PZR
- Additional structures to enhance mixing inside RPV (get uniform thermal hydraulic conditions at core inlet, relevant in case of SLB-accidents)
  - SMART design

Consequences:

- Flow patterns inside RPV perturbed by structures
- Mixed convection flow
- 3D flow conditions

➔ 1D thermal hydraulic codes are not able to properly describe these conditions

McSAFER Solution Approach:

- Industrial tools:
  - 1D / 3D coarse mesh TH codes
- Research tools:
  - Multiscale coupling of system TH with subchannel-codes
  - Multiscale coupling of system TH with CFD-codes

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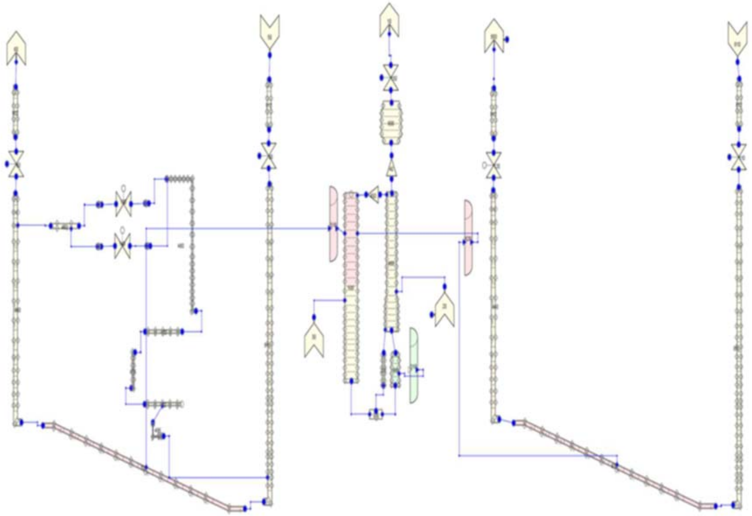
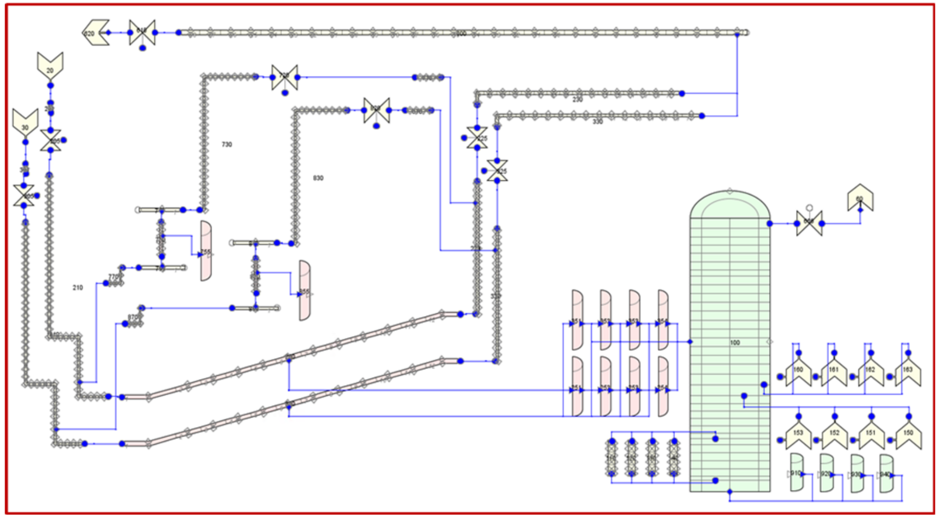
JRC: NuScale from 1D to 3D Thermal Hydraulics (TRACE)



1D TRACE Plant Model



1D/3D TRACE Plant Model

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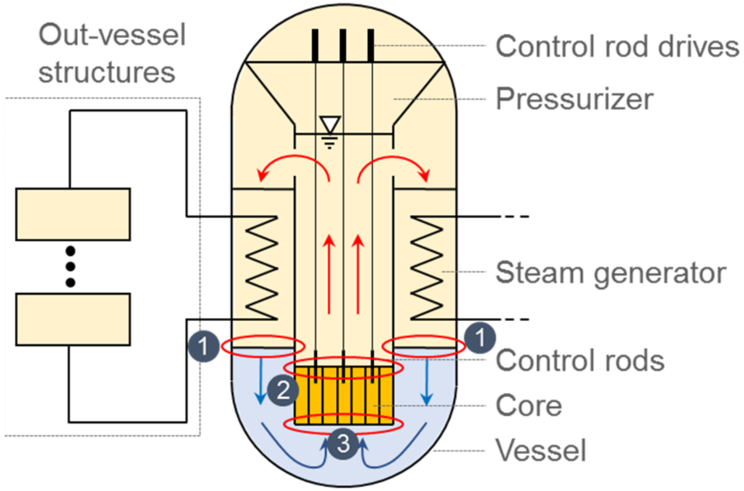
Karlsruhe Institute of Technology

McSAFER Multicale/Multiphysics Tools: RPV and Plant Analysis



1 Interface between TRACE and CFD
2 Interface between TRACE and SCF
3 Interface between CFD to SCF

- RPV multiscale approach for improved thermal hydraulic simulations:

System TH: TRACE, ATHLET, RELAP5-3D, APROS

Core TH: system TH, subchannel codes: SCF, VIPRE, ARTHUR, COBRA-TF

CFD e.g. OpenFOAM, TrioCFD, FLUENT

Core neutronics: Point kinetics, 3D Diffusion solvers

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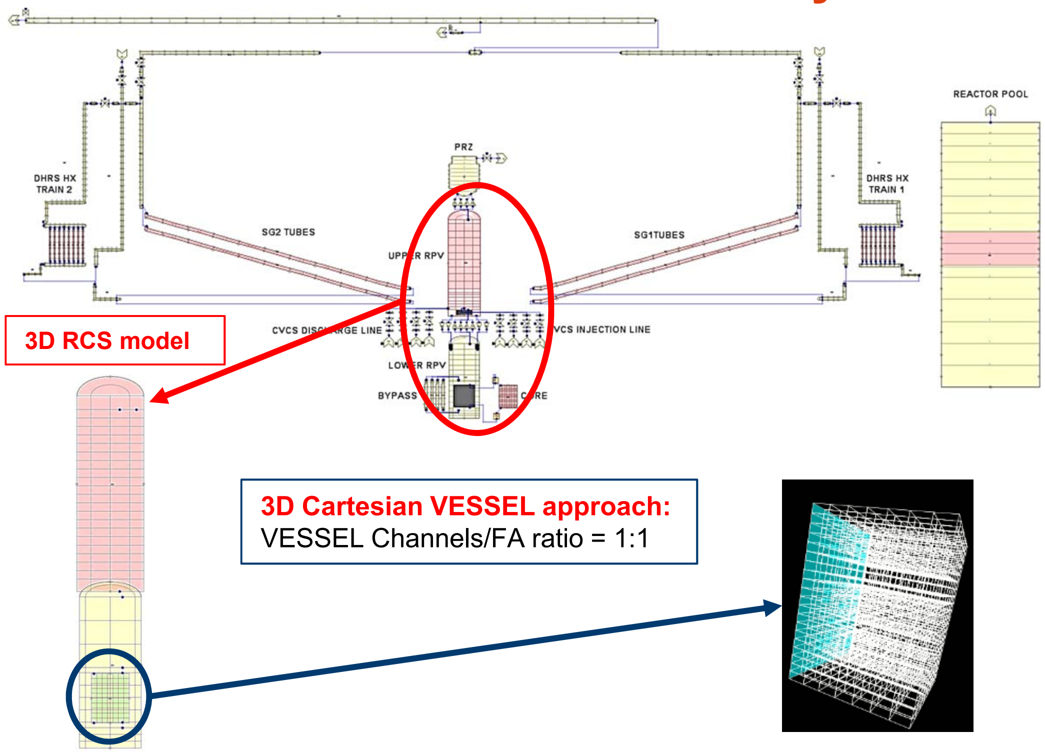
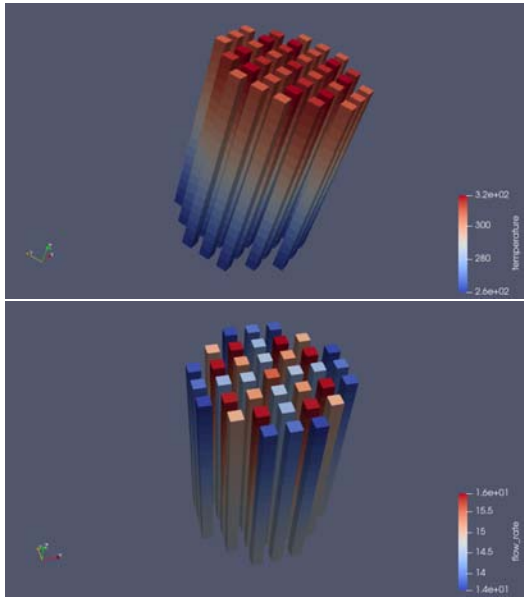
UPM: NuScale Multiscale TH by TRACE/Subchanflow



UPM 1D/3D NuScale Model

TRACE-SCF coupling scheme developed by KIT is applied in the UPM multiscale approach



UPM: TRACE 3D-SCF NuScale Model

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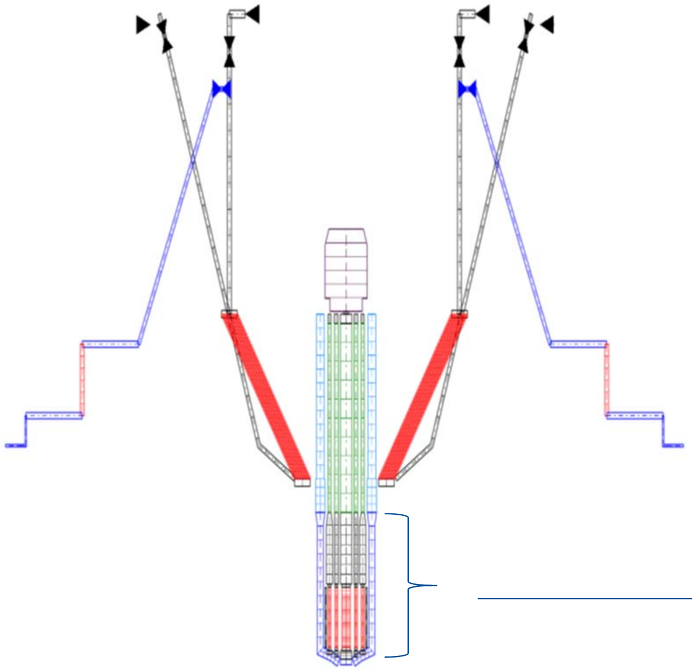
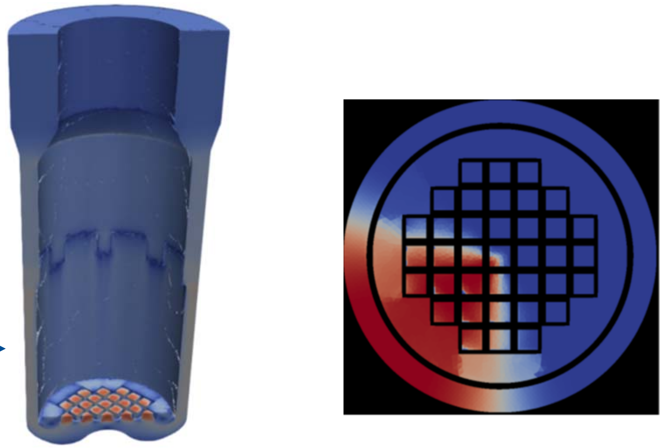
HZDR: NuScale Multiscale TH: ATHLET/TrioCFD



NuScale SMR: 1D/3D Thermal Hydraulics Model



TrioCFD Model of Downcomer and lower plenum

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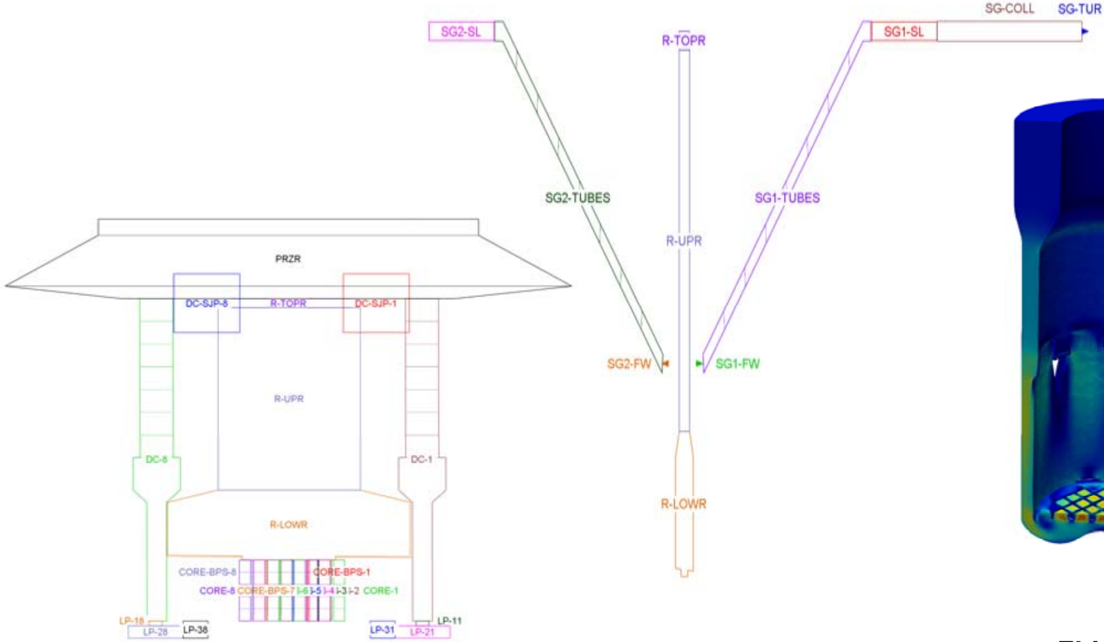
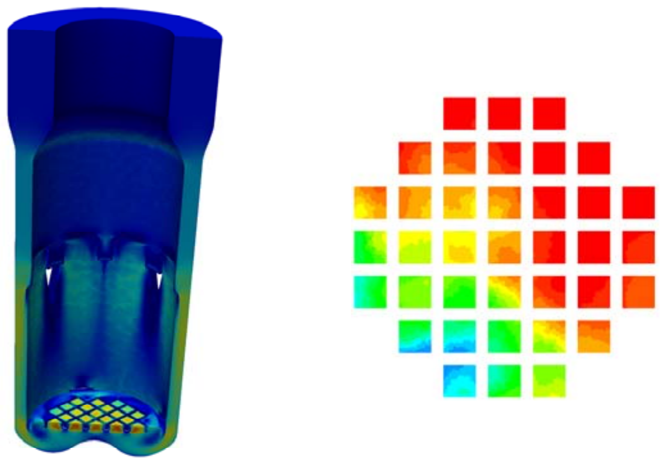
UJV: NuScale Multiscale Thermal Hydraulic Model



ATHLET Thermal Hydraulics Model



FLUENT: 3D Thermal Hydraulics model of downcomer and lower plenum

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Challenges IV: Integral Plant Analysis under postulated DBA

Challenges:

- Many components located inside the RPV
  - Pumps: e.g. SMART (8)
  - Helical HX e.g. SMART(8), CAREM (12)
  - PZR
- Additional structures to enhance mixing inside RPV (get uniform thermal hydraulic conditions at core inlet, relevant in case of SLB-accidents)
  - SMART design

Consequences:

- Flow patterns inside RPV perturbed by structures
- Mixed convection flow
- 3D flow conditions

➔ 1D thermal hydraulic codes are not able to properly describe these conditions

McSAFER Solution Approach:

- Industrial tools:
  - 1D / 3D coarse mesh TH codes
- Multiphysics / multiscale approach:
  - Coupling of systemTH/Subchannel and 3D Diffusion solvers e.g. TRACE/PARCS/SCF
  - SystemTH/Subchannel and 3D Diffusion solvers e.g.
    - TRACE/PARCS/OpenFOAM
    - ATHLET/DYN3D/TrioCFD
    - TRACE/ANTS/OpenOFAM
    - ATHLET/DYN3D/FLUENT

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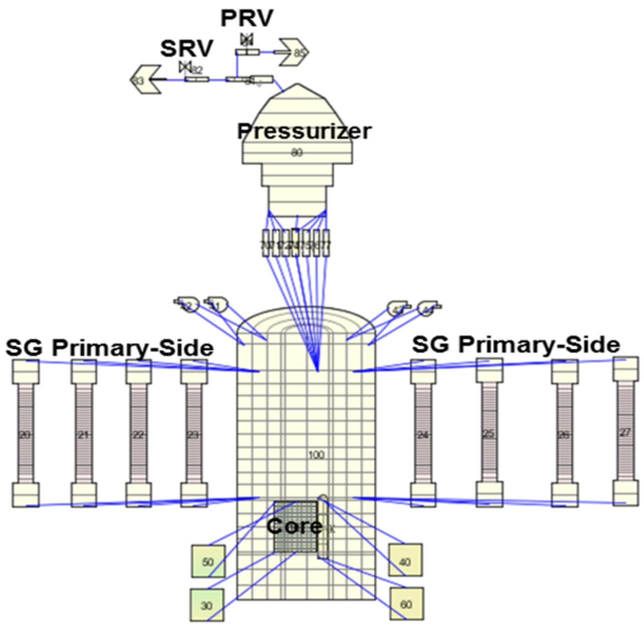
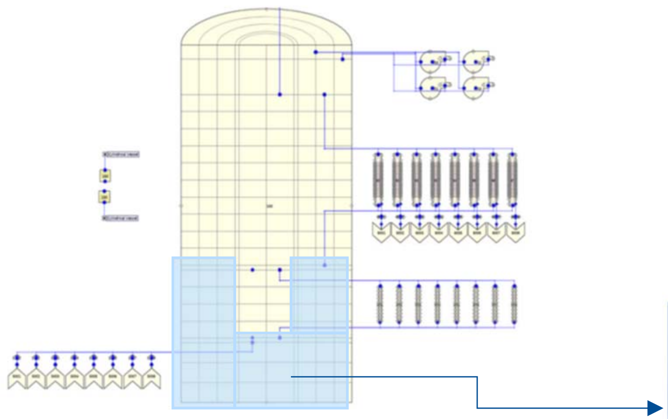
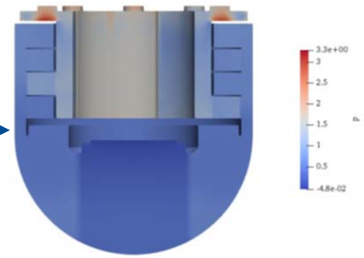
KIT Analysis Approach: TRACE/PARCS/OpenFOAM



TRACE Domain: Core + RPV + Plant



TRACE Domain: Core + RPV



OpenFOAM Domain

ICoCo-based TRACE-OpenFOAM and PARCS/TRACE coupling

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

McSAFER Education & Training, Dissemination

- Training courses:
  - First training course on SMR Technologies: January 25-27.2021: UPM
    - Participants: 194
  - Second training course on SMR neutronics and thermal hydraulics: March 22-24, 2022: LUT
    - Lectures on simulation methods, Demonstration of Kraken Multiphysics framework, TH laboratory activities
    - Participants:
      - 17 students at LUT,
      - total 44 incl. lecturers and online participants (first day was streamed)
  - MOOC course on Multiphysics simulations applied to SMR (march 2023): UPM
- Mobility program
  - 9 fellowships **to be assigned for mobility of young researchers**
    - **See: https://mcsafer-h2020.eu/news-and-events/**
    - Still SEVEN fellowships available!

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McSAFER Coordinator

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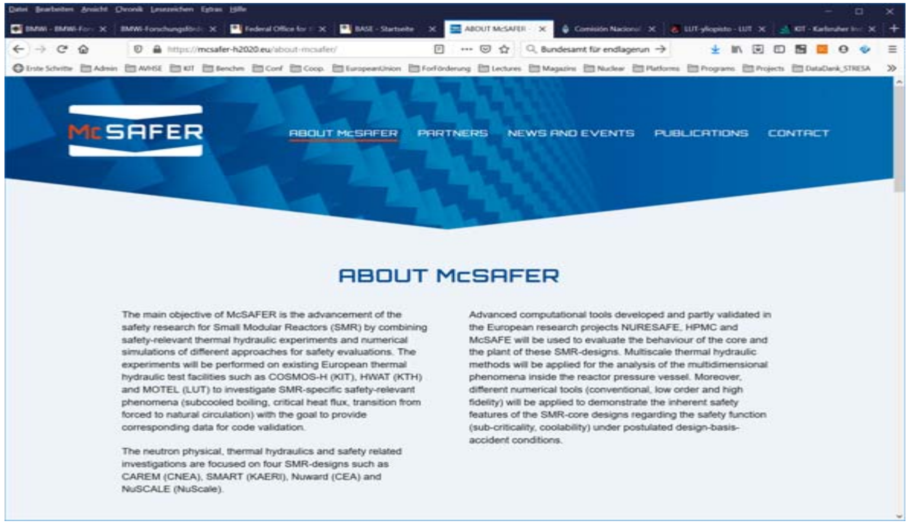
KIT CN Karlsruhe



Visit website: www.mcsafer-h2020.eu

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