Specific Aspects of Reactor Safety Research at KIT

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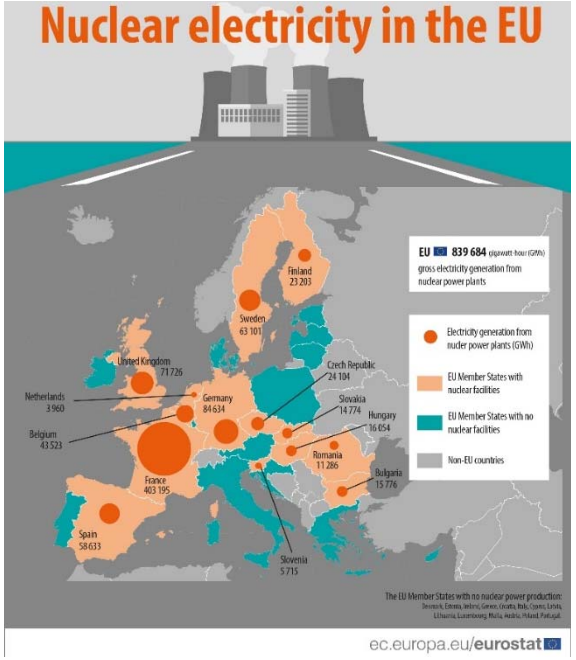
Reactor Physics and Dynamic Group (RPD)

Motivation: NUSAFE Program at KIT

- Different NPPs operating and going to be built in EU and worldwide.
- No ‘Zero-Risk’ Technology.

- **Mission:**
  - **Expertise preservation to assess the safety of any reactor system**



- Milestones:
- **Safety assessment of NPPS including innovative designs** (LWR, SMR, Gen-IV, MYRRHA) within European projects, International cooperation's, and International boards, e.g. IAEA and OECD/NEA.
- **Improvement of Severe Accident integral codes** → support Severe Accident Management Guidelines (SAMGs).
- Multi-criteria Decision Analysis (**MCDA**) and Agent Based Modeling (**ABM**) → **supporting decision making** under high uncertainties for all emergency situations.

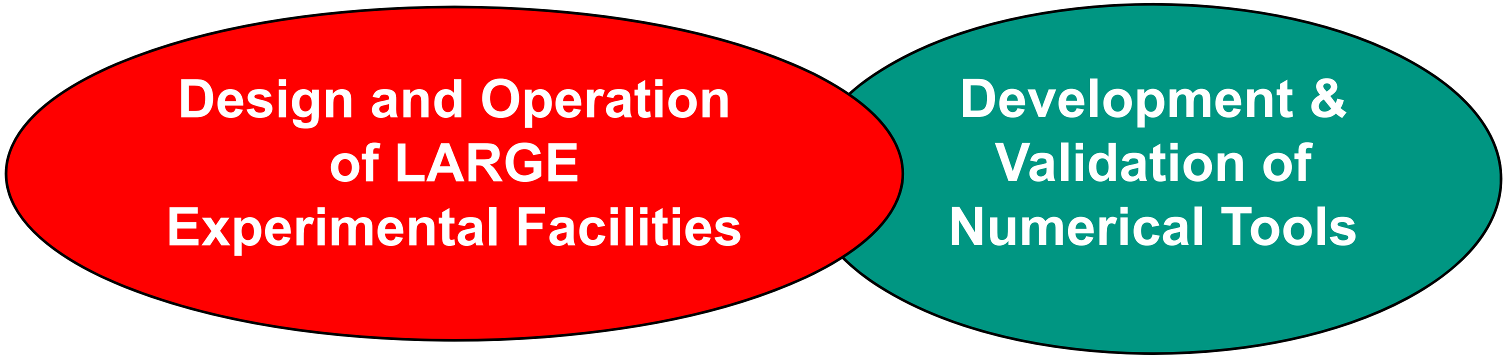
Motivation: NUSAFE Program at KIT (Reactor Safety)

Topic 2: Reactor Safety

Subtopic 2.1: Reactor Operation and Design Basis Accidents

Subtopic 2.2: Beyond Design Basis Accidents and Emergency Management

HGF Peculiarity:



- **KIT as unique research campus for clustering experiments, developers, modelling research teams, and knowledge preservation.**

- Integral tests and separate effect tests employed for the validation, uncertainty quantification, and development of the codes.

KIT Strategy: Numerical Tools and Experiments

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- **The Safety Demonstration is mainly based on Numerical Tools and Reference experiments.**

- Tools and experiments must reflect the *State-of-the-art*, which is determined by research community → Continuous improvement is a must.

- Strategy:
  - Combination of innovative research and education and training
  - Combination of in-house and foreign codes

- Moving to innovative research directions:
  - Advanced physical models and mathematical methods ← **Experiments**
  - High-fidelity simulations and multi-scale procedures
  - Uncertainty quantification ← **Experiments**
  - V&V, application, and analysis ← **Experiments**
  - Massive use of High Performance computing (HPC)

KIT Strategy for Reactor Safety (LWRs)

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Design Basis Accidents

- EU NURESIM Platform (CEA)
  - European Platform for Reactor Simulations (CEA, EDF, Framatome)
  - Multi-physics and scale simulations: neutronics, TH, and TM
- US NRC Intern. CAMP (>20 years)
  - Reference codes for Gen-II/III NPPs:
  - TRACE, PARCS, SCALE
  - U&S tools: DAKOTA
- In-House code development
  - High Fidelity codes based on Monte Carlo
  - Multi-physics and multi-scale coupling

Beyond Design Basis Accidents

- Accident Source Term Evaluation Code (ASTEC, IRSN)
  - KIT: Code development, application, Uncertainty Methods
- MELCOR
  - Code benchmarking
  - Coupling with KIT codes

Radiological Source Term

- Emergency Management
  - JRODOS

COSMO-H, WENKA, QUENCH-LOCA

Experiments

QUENCH, LIVE, MOCKA, DISCO, HYKA

KIT Facilities for Reactor Safety

- **Design Basis Accident Research**
  - **LWR TH and Safety**
    - **COSMOS-L** and **COSMOS-**H (CHF water)
    - **WENKA** (Counter-current flow in horizontal pipes)
  - **GEN-IV Thermal hydraulics, Materials and safety**
    - **L-STAR** (Helium loop)
    - **KALLA-Bundle test** (Lead Heat transfer and pressure drop)
    - **KASOLA** (Sodium loop)
    - **COSTA, CRISLA, THEADES** (Materials, components)

- **Severe Accident research**
  - **LWR in-vessel phenomena**
    - **QUENCH** (early phase: reflooding of degraded bundles)
    - **LIVE** (molten material in RBD-lower plenum)
  - **LWR: ex-vessel phenomena**
    - **MOCKA** (MCCI: molten corium concrete interactions)
  - **LWR Containment phenomena**
    - **HYKA**, Hydrogen Safety Test Centre (H2 distribution and combustion in large range of geometrical and energetic scales)
    - Detonation Tube (H2 detonation tests)
    - Flow test chamber (vented combustion and detonation, shock waves)

Reactor dynamics and accident analysis: Thermal Hydraulics Code Development

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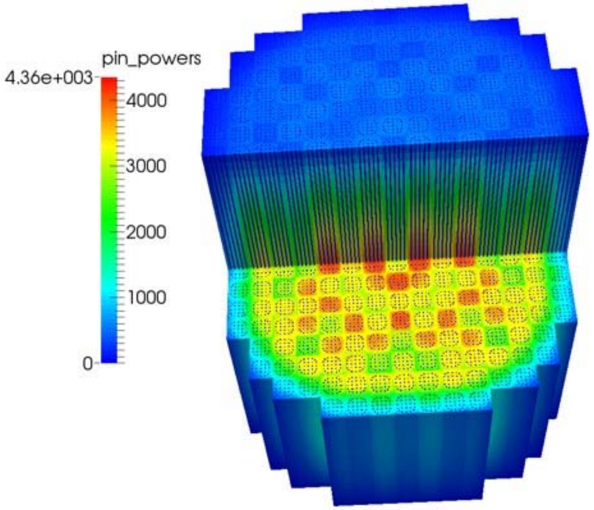
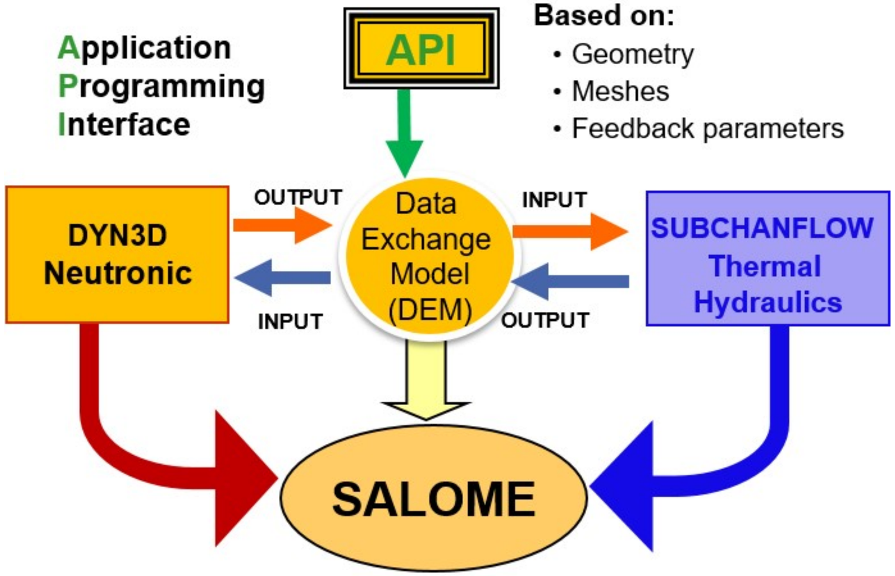
SUBCHANFLOW Code (In-house):

- Fast running code with flexible geometry
- Diverse working fluids (water, gas, liquid metals)
- Coupled with different neutronics, thermo-mechanic and thermal-hydraulics codes



Full PWR Core SERPENT2/SCF Solution

Part of the EU NURESIM Platform



NURESIM- Platform: Code coupling Strategy

EU NURESAFE (2013-2016)

EU McSAFE (2017- 2020) coordinated by KIT

A. Ivanov et al., Annals of Nuclear Energy, 2015, http://dx.doi.org/10.1016/j.anucene.2014.12.030

COSMOS Facilities

Critical Heat Flux On Smooth and MOdified Surfaces

- Investigations on Critical Heat Flux (CHF) and its dependency to the thermodynamic boundary conditions and material properties.
- Unique experimentation possibilities in the water cycle under high pressure and high temperature conditions (optical access to the heated section up to 170 bar).

COSMO-L

System Pressure	1 – 3 bar
Mass flow test section	0.01 – 0.8 kg/s
Inlet T	45 – 120 °C
Heating Power	Up to 300 kW

https://www.ites.kit.edu/128.php

https://www.ites.kit.edu/625.php

COSMO-H

System Pressure	70-170 bar
Max. Press. Difference (Pump)	10 bar
Steam Mass Fraction (inlet)	0-30 %
Mass flow (Liquid Water+steam)	~1.4 kg/s
Mass flow density	4000 kg/m^{2}s
Max. Inlet T	360 °C
Max. Heating Power	1.8 MW

McSAFE – High Performance Monte Carlo Methods for SAFEty Demonstration

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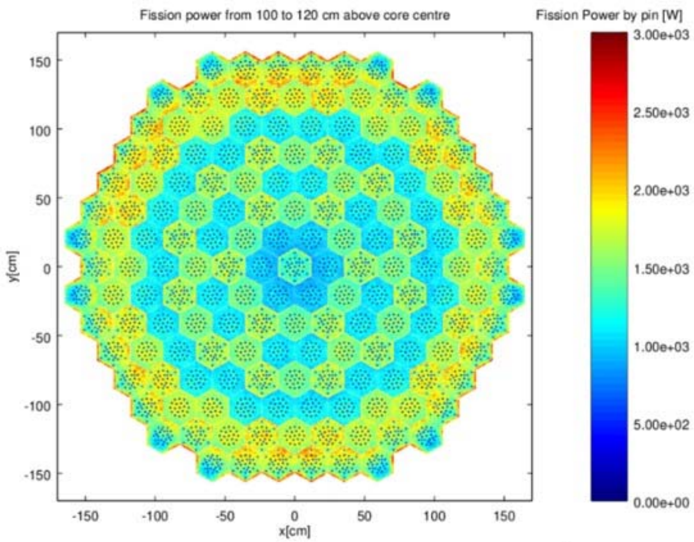
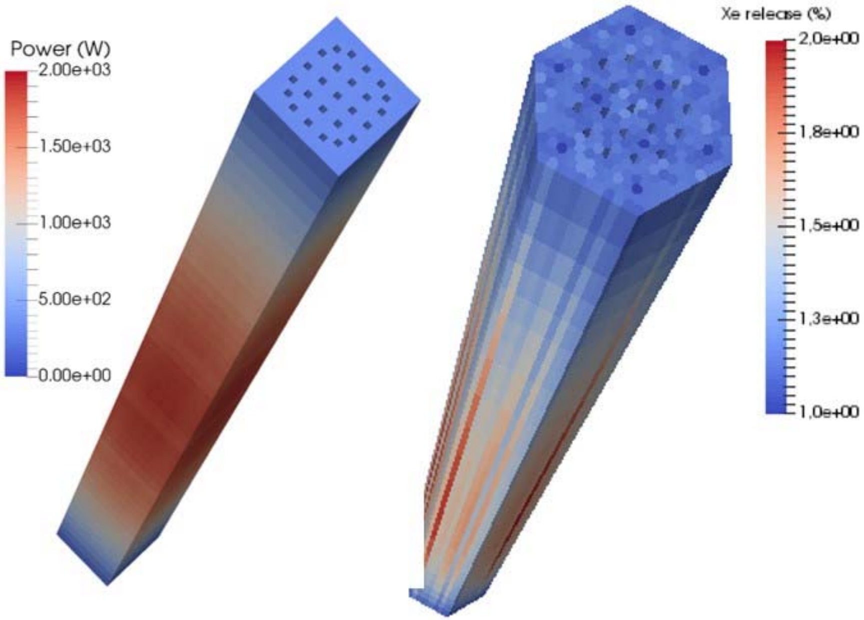
H2020

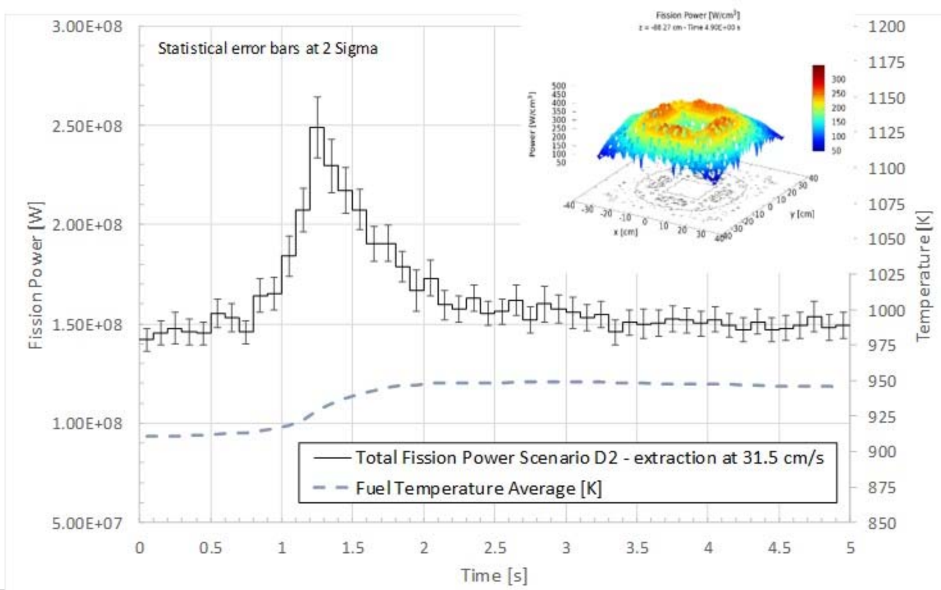
McSAFE

High Performance Monte Carlo for Safety

- Serpent2/SubChanFlow/Transuranus
- Fully coupled pin-by-pin full-core depletion and transient cases.
- Validation with PWR and VVER experimental data.







INR

Coming EU H2020 Projects (1.9.2020-31.8.2023)

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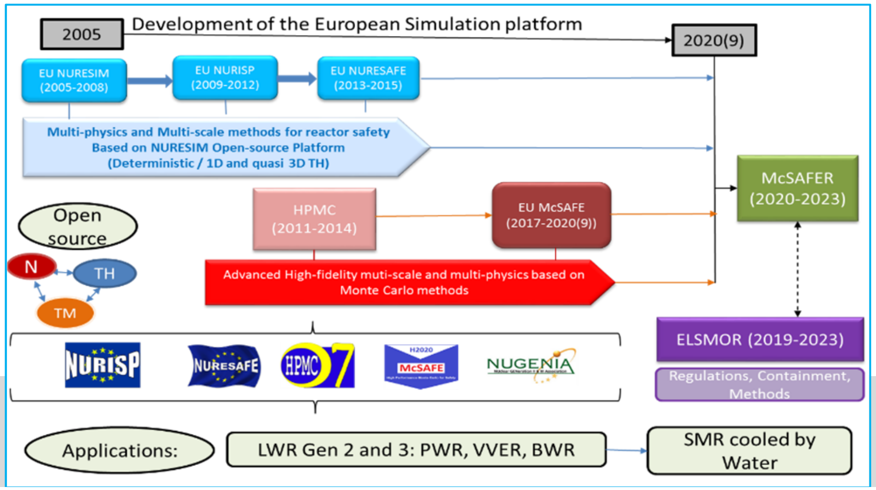
- **H2020 McSAFER**: High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic **Small Modular Reactors**
  - Core physics (Deterministic, MC-based Multiphysics)
  - RPV TH: Multi-scale TH (CFD, sysTH, subTH)
  - Transient analysis: traditional and advanced methods including t-dependent MC
  - **Coordinator**: KIT (V. Sanchez)
  - 13 partners: KIT, LUT, VTT, CEA, KTH, HZDR, PEL, TRACTEBEL, WOOD, UPM, CNEA, UJV, JRC Ka

Roadmap for the implementation of the McSAFER tools in the European context

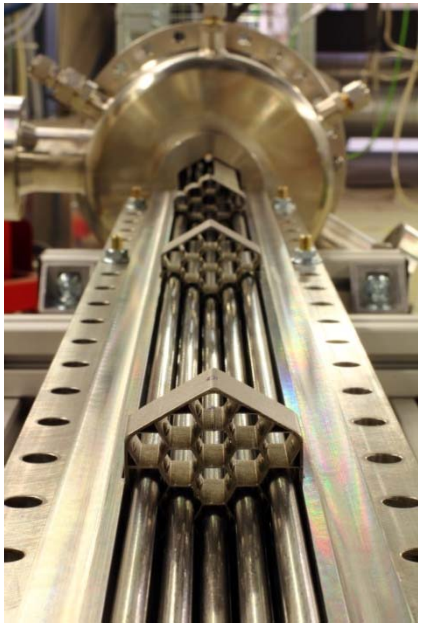


- **H2020 CAMIVVER**: Codes and Methods Improvements for **VVER** comprehensive safety assessment
  - Core neutronics (Deterministic, MC-based Multiphysics)
  - Core TH (subchannel, system, CFD)
  - RPV TH: Multi-scale TH (CFD, sysTH, subTH)
  - Advanced accident analysis (system TH with 3D coarse mesh, coupled codes with 3D KN and 3D TH
  - **Coordinator**: FRAMATOME
  - 7 partners: FRAMATOME, INRNE, CEA, EDF, KIT, ENERGORISK, UNUPI

Gen-IV Systems

Experimental investigations

- Several reactor liquid metals
  - Thermal-hydraulic investigations
  - Material research on corrosion behavior and protective layers



Code development

- **Initiation Phase**
  - **SAS-SFR**, **PARCS/SAS-SFR**
- **Transition Phase and Late Phase**
  - **SIMMER III-IV**: developed by JAEA + CEA + KIT originally for SFR
  - **ASTEC-Na**
- CEA and KIT together coordinate activities in Europe, e.g. KIT for ADS/LFR extensions

Pacio, J. et al (2018) Heat transfer experiment in a partially (internally) blocked 19-rod bundle with wire spacers cooled by LBE . Nuclear Engineering and Design 330, 225-240
Jianu, A. et al (2016) Stability domain of alumina thermally grown on Fe-Cr-Al-based model alloys and modified surface layers exposed to oxygen containing molten Pb. Journal of Nuclear Materials 470, 68-75

Materials Research: QUENCH-LOCA

- Motivation
  - Cladding embrittlement criterion taking into account oxygen <u>and</u> hydrogen
  - Mechanical properties of cladding tubes and the influence of secondary hydrogen uptake
- 2011-2016, seven LB-LOCA experiments
  - supported by German industry
- Results:
  - Coolability of the bundles ensured
  - Residual strength and ductility sufficient
  - Channel blockage less than 25%
  - But secondary hydrogen uptake observed

Neutron tomography image

J. Stuckert et al., Nucl. Eng. Des., 2013, DOI: 10.1016/j.nucengdes.2012.10.024
Grosse, M., Stuckert, J., Roessger, C., Steinbrueck, M., Walter, M., Kaestner, A. Analysis of the secondary cladding hydrogenation during the quench-LOCA bundle tests with zircaloy-4 claddings and its influence on the cladding embrittlement (2015), ASTM Special Technical Publication, STP 1543, 1054-1073.

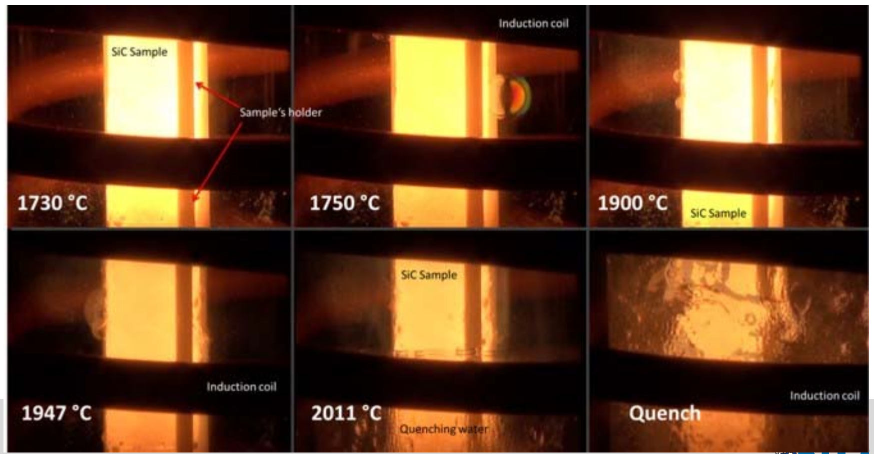
QUENCH Tests on Accident Tolerant Fuels

- **High-temperature oxidation of ATF claddings**
  - Small-scale separate-effects tests
  - Single-rod experiments including quench phase
  - Large-scale bundle tests
    - FeCrAl test with ORNL on 2017
    - SiC under discussion with Westinghouse

- OECD-NEA Expert Group on Accident Tolerant Fuels for LWRs
- IAEA CRP on Accident Tolerant Fuel Concepts for Light Water Reactors (ACTOF)
- EC project IL TROVATORE (H2020)

SiC-SiC$_f$ cladding after 64 h at 1600°C in steam

QUENCH bundle for large-scale experiments

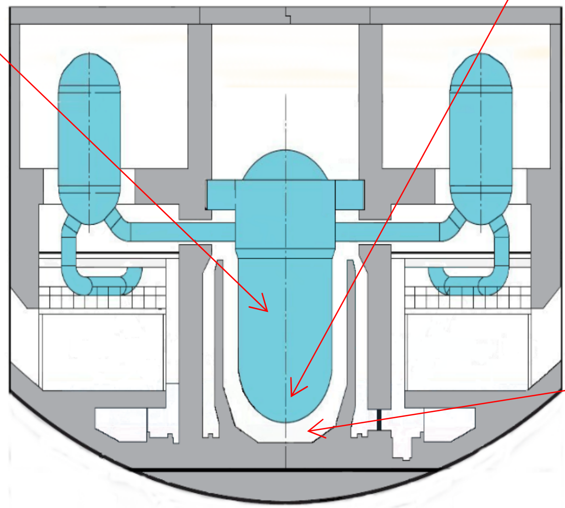


Sever Accidents KIT Facilities

Core coolability and debris cooling

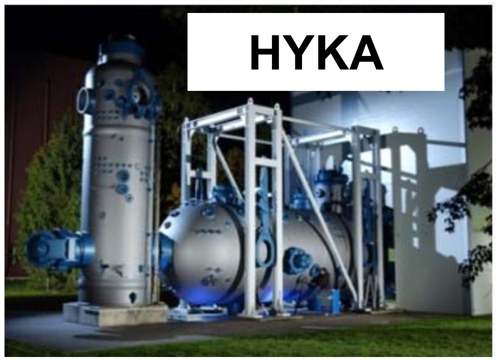
QUENCH

In-vessel melt retention



Molten Corium Concrete Interaction

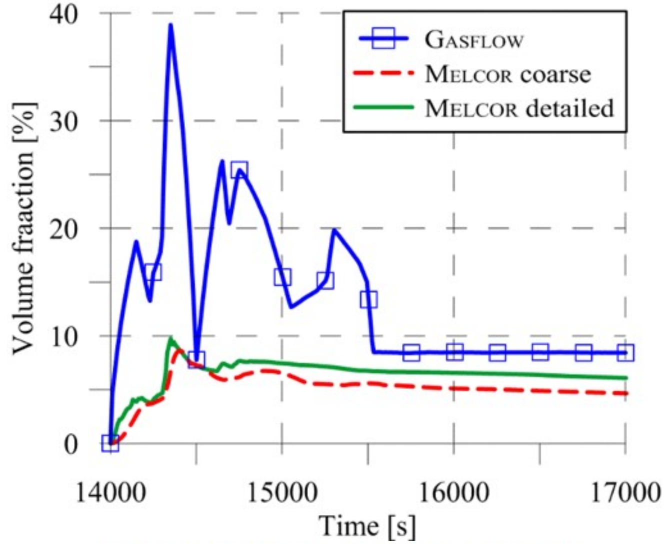
MOCKA

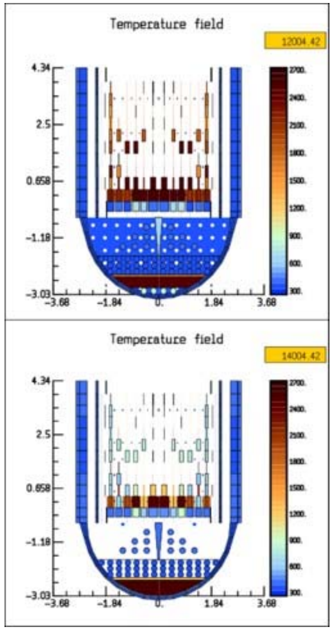


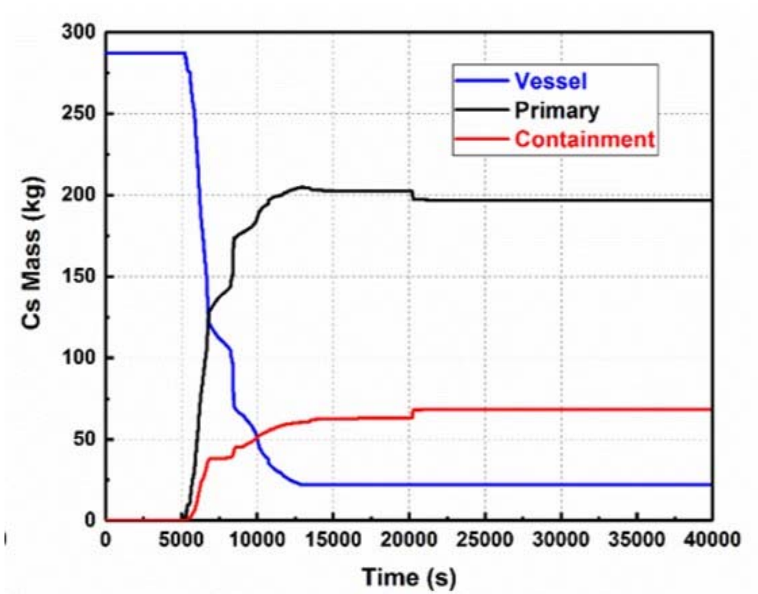
A. Miassoedov et al, Heat Transfer Eng., 2013, DOI: 10.1080/01457632.2013.777247.
M. Steinbrück et al., J. Nucl. Mater., 2017, DOI: 10.1016/j.jnucmat.2017.04.034
Tang, C., Stueber, M., Seifert, H.J., Steinbrueck, M. Protective coatings on zirconium-based alloys as accident-Tolerant fuel (ATF) claddings (2017), Corrosion Reviews 35, 141-165.

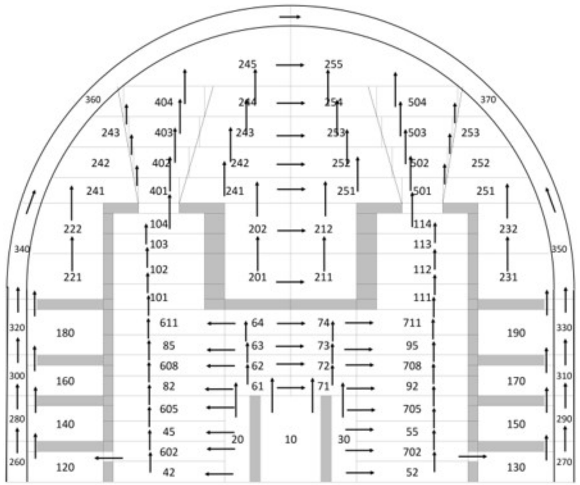
Severe Accident Analysis

- KIT experimental facilities for validation of in-house and international codes
- Code coupling of integral codes with CFD codes
- **Code application for improvement of Severe Accident Management Guidelines (SAM-G)**









F. Gabrielli, V. Sanchez, ASTEC Evaluation of the Radiological Source Term in a generic PWR Konvoi 1300 Plant, 9th ASTEC User's Club Meeting, KIT CN, 2019, September 24-26.
T. Szabó, F. Kretzschmar, T. Schulenberg, (2014), Obtaining a more realistic hydrogen distribution in the containment by coupling MELCOR with GASFLOW. Nuclear Engineering and Design, 269
I. Gómez García-Toraño, et. al (2017). Investigation of SAM measures during selected MBLOCA sequences along with Station Blackout in a generic Konvoi PWR using ASTECV2.0. Annals of Nuclear Energy, 105, 226–39.

KIT Strategy for SA codes

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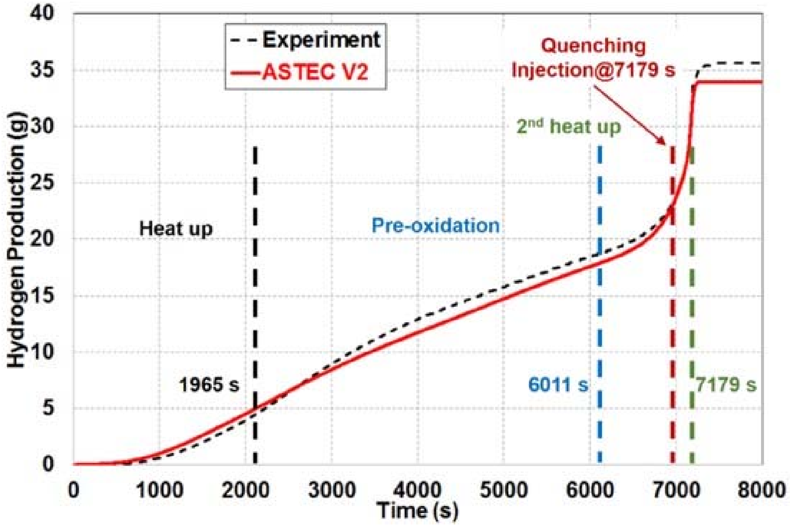
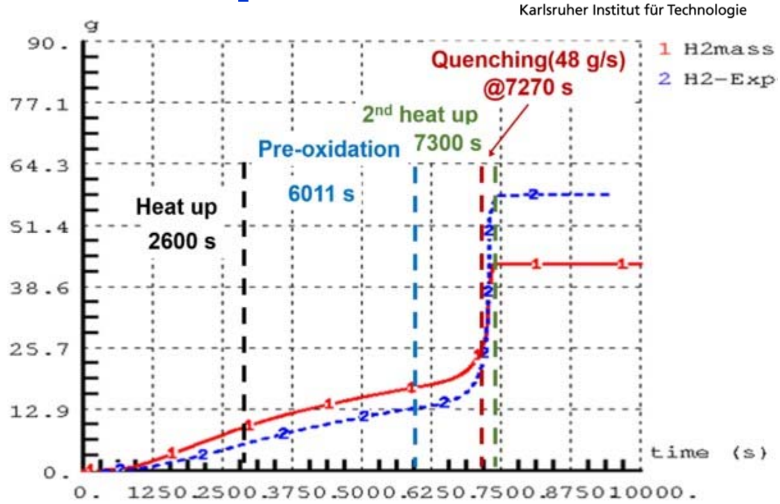
- Fukushima accidents showed necessity for
  - Re-evaluating accident analysis methods, SAMGs, and plant status
  - Improving the numerical simulation tools e.g. ASTEC, MELCOR, etc.

- **Code development, validation and application**
  - **V&V** of SA codes, e.g. ASTEC and MELCOR
  - **SA codes extension – continuous interaction with developers → strategic cooperation's with IRSN and USNRC**
  - Coupling of integral codes with CFD codes, e.g. MELCOR/GASFLOW, ASTEC/JRODOS
  - **Evaluation of the Radiological Source Term**
  - **Application of U&S methods to SA codes**, e.g. URANIE, SUNSET, in-House tools
  - Applications of SA Codes for **SAMs assessment**
  - **Knowledge preservation/dissemination (PhDs and Master programs)**

ASTEC Code Validation @KIT: Examples

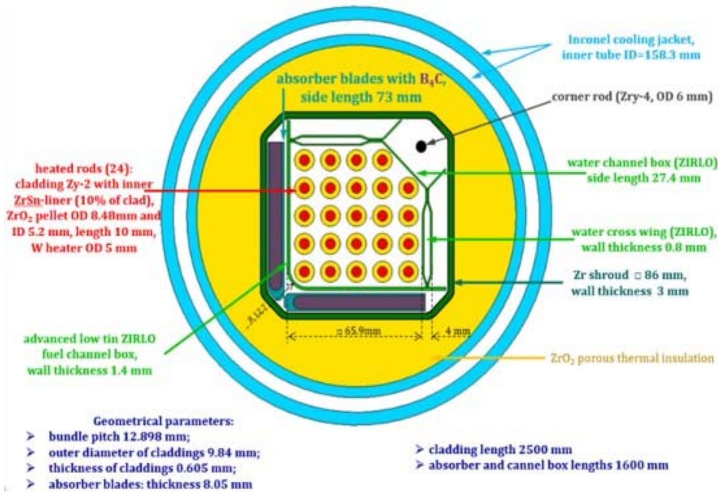


QUENCH-06 (PWR)



QUENCH-12 (VVER)

- **QUENCH-20**: high temperature degradation of BWR assembly mock-up, e.g. melt formation due to eutectic material interaction inside absorber cross.
- **QUENCH-19: bundle tests with FeCrAl claddings.**



K. Mercan, V. H. Sánchez-Espinoza, F. Gabrielli, Validation of ASTEC2.1 using QUENCH-12 for VVER-Reactors, Proc. of ERMSAR 2019, March 18th-20th, Prague.

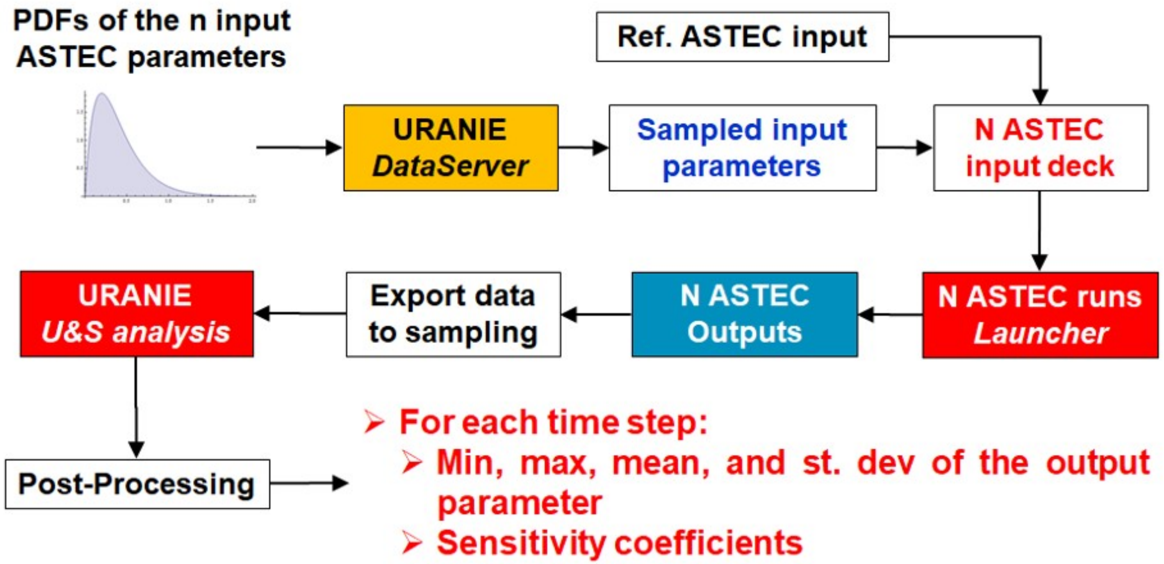
J. Stuckert, A. Goryachev, M. Große, M. Heck, I. Ivanova, G. Schanz, L. Sepold, U. Stegmaier, M. Steinbrück, "Results of the QUENCH-12 Experiment on Reflood of a VVER-type Bundle," Forschungzentrum Karlsruhe in der Helmholtz-Gemeinschaft, Karlsruhe, 2008.

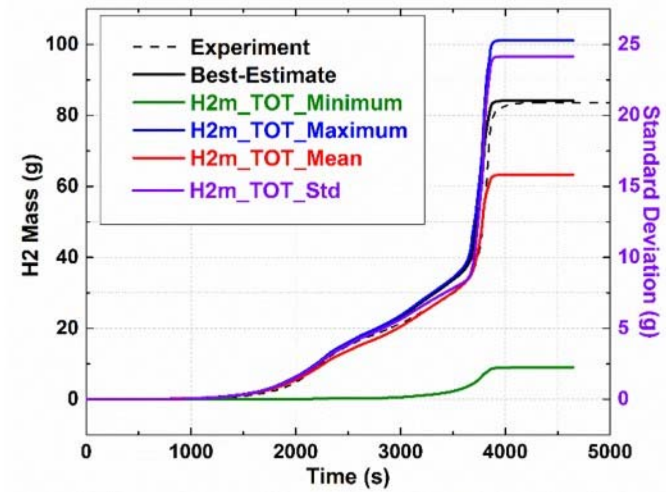
U&S-Tools and related Codes @KIT

- **Applied methods:**
  - **SUSA (GRS)**
  - **URANIE (NURESAFE Framework)**
  - **DAKOTA (CAMP Framework)**
- **Performed applications:**
  - **TRACE / SUSA**
  - **TRACE / DAKOTA**
  - **CTF / URANIE**
  - **SUBCHANFLOW/URANIE**
- **SA Application:**
  - **URANIE/ASTEC**
- **Further developments:**
  - **URANIE/TRACE**
  - **URANIE/TRANSURANUS**
  - **URANIE/PARCS**

U&S Analyses of SAs investigations

- The improvement of the performance of the BE system codes for analyzing operational and SA scenarios is a continuous on-going process.
- The use of Uncertainty & Sensitivity (U&S) tools for validating the complex physical models employed in such a codes plays an important role.
- ..which becomes **fundamental when SA analyses are considered**, because of the large uncertainties associated to the physical models employed, e.g., the MELCOR, MAAP, ASTEC Xwalk studies on 1F1.





F. Gabrielli, V. Sanchez, Uncertainty and Sensitivity Analysis by means of ASTEC/URANIE Platform of the QUENCH-08 Experiment, 24th International QUENCH Workshop, KIT CN, 2018, November 13th -15th, DOI: 10.5445/IR/1000088229.

SAs-Related Projects

- **EU Management and Uncertainties of Severe Accidents (MUSA) Project (2019-).**
- **Assessing the capability of SA codes when modelling SA scenarios for Gen. II/III/III+ reactor designs and SFPs by using the UQ methods.**
- **Effect of existing/innovative SAMs** on accident progression and **ST mitigation**.
  - **Phébus, PWR, VVER**

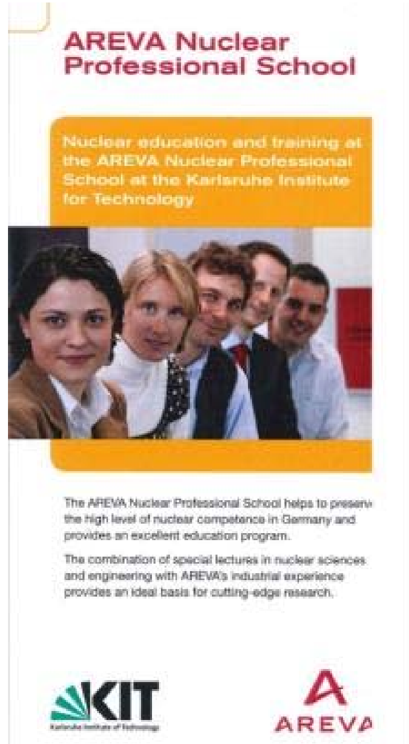
- **ASTEC COMmunity (ASCOM) project**
- **Supporting the IRSN ASTEC code as a fully reliable tool for SA analyses and SAM in a wide range of nuclear safety applications**.
  - **PWR, BWR, VVER, QUENCH Analyses**

- **WAME Project (2019-2023):** ‘*Maintaining competence in nuclear technology (KEK) of the Federal Ministry of Economics and Technology (BMWi)*’
- **Development of a novel real-time program system to improve decision making in severe accident events in nuclear power plants (PhD)**.

- **IAEA CRP I31033 on U&S Methods for SA Analysis in Water Cooled Reactors (2019-2024) ← QUENCH-06 employed for Experimental case**

Education & Training

- KIT Lectures on neutronics, thermal hydraulics and reactor safety
- Hosting foreign students (Erasmus, Leonardo da Vinci, DAAD, internships,…)
- Doctoral students financed by partners e.g. Industry, DAAD, EU/national projects
- Post-gradual courses e.g. FRAMATOME Nuclear Professional School: http://www.fps.kit.edu/
- Frederic Joliot Otto Hahn (FJOH) Summer School (www.fjohss.eu)



Summary

- Safety Research at KIT based on both Large Scale Experiments and Modelling.
- **KIT experiments cover both LWRs and innovative reactors for:**
  - **Design Basis Accident**
  - **Beyond Design Basis Accident**
- Key activities:
  - Improving the Sate-of-Art
  - Providing data for code validation
  - Performing validation of codes and developing own tools
- Research activities embedded in national and international co-operations.
- Strategic partnerships with important key-players.
- Education and Training Program.