# KIT Numerical and Experimental Investigations for LWR Reactor Safety


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# Outline

- Motivation
- Challenges
- LWR experimental investigations for safety
- LWR numerical simulations for Design Basis Accidents
- LWR numerical simulations for severe accidents

# Motivation

- Nuclear energy use for electricity generation ends in 2022 in Germany

- Dismantling of Nuclear Power Plants will last for decades
  - Expertise in nuclear power plants, reactor physics, radiation protection, etc. is needed

- Construction of reactors around Germany and worldwide
  - Nuclear countries
  - Emerging countries
  - Developing countries

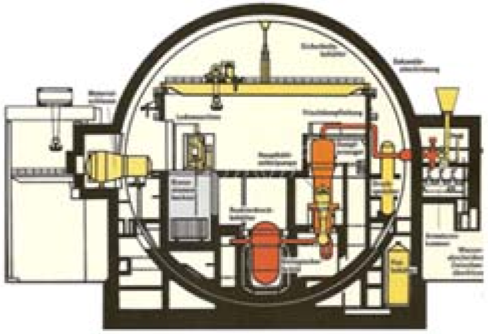

| | |
|---|---|
| Philippsburg II | 2019 |
| Brokdorf | 2021 |
| Grohnde | 2021 |
| Gundremmingen C | 2021 |
| Isar II | 2022 |
| Neckarwestheim II | 2022 |
| Emsland | 2022 |

- Necessity to keep EXPERTISE to assess SAFETY of any reactor system
  - Major mission of the **Helmholtz Association of Large Research Centres** (HGF). KIT is part of it.

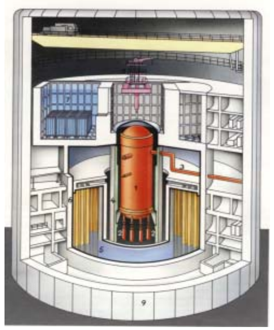
# Challenges

# Challenges (1/3): Different Reactor Designs

Gen- II LWR:

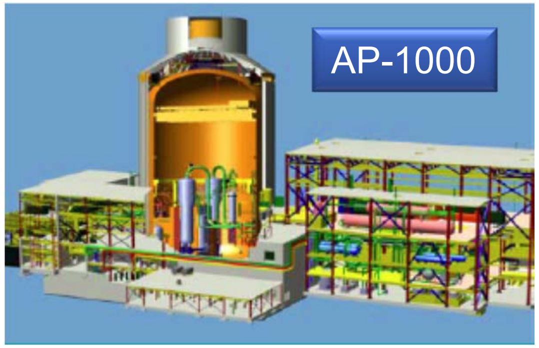


PWR Konvoi

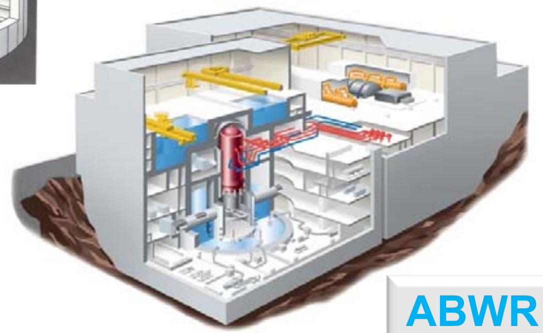


BWR Type-72

Gen- III LWR:

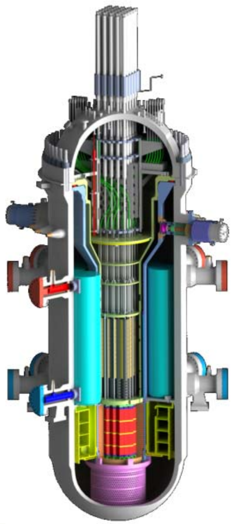


AP-1000

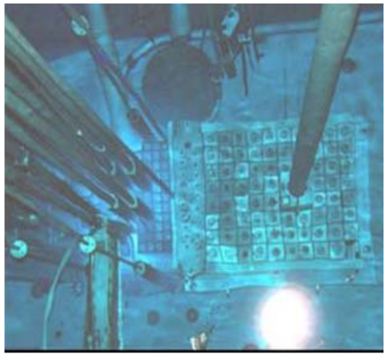


ABWR

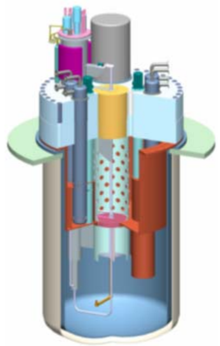
Innovative Reactors:



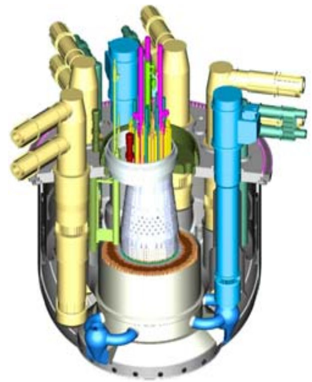
SMR SMART



Research Reactors



LFR (ADS)



SFR

# Challenge (2/3): Reactor Safety

- No “Zero Risk” technology: Fukushima Severe Accident



- SAFETY DEMONSTRATION based mainly of NUMERICAL TOOLS
  - Continuous improvement (state-of-the-art)
  - Verification & Validation & Uncertainty quantification

Main goal of international nuclear community:
Prevent any accident  including SEVERE ACCIDENT !!

# Challenge (3/3): How to Validate Numerical tools?

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- Experimental investigations
  - Fundamental research: Separate effect test
  - Integral tests
  - Test in nuclear reactors

Define State-of-the-art ⟷ Regulations, Safety demonstration

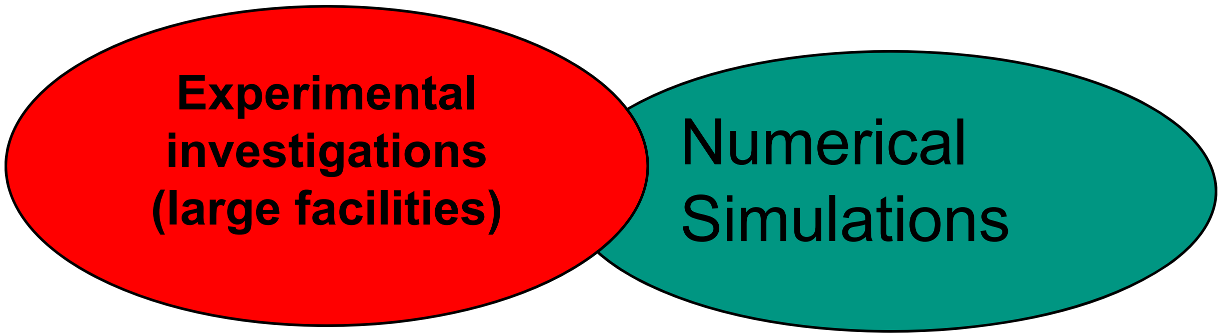
- Moving from LEGACY CODES to "HIGH FIDELITY" SIMULATIONS
  - Solve first-principles equations
  - Increase spatial discretization: 1D/3D Coarse MESH → 3D fine mesh / unstructured grids
  - Higher order numerical methods
  - Reduce conservatism

Main Driver: Huge and cheap computer power available worldwide, also in Germany (e.g. KIT: High Performance Computers for Energy Research)

# HGF NUSAFE Program at KIT

- **Topic 1: Nuclear Waste Management**
  - Subtopic 1.1: Safety Research for Nuclear Waste Disposal
  - Subtopic 1.2: Waste management strategies
- **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

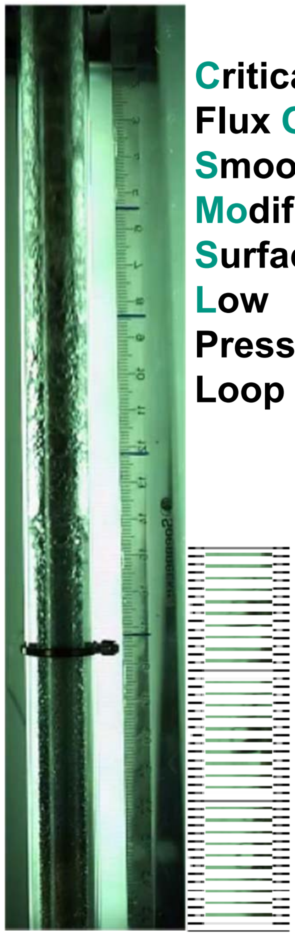


# LWR Experimental Investigations for SAFETY

# Reactor dynamics and accident analysis: Thermal Hydraulics Experimental Facilities

DBA

## COSMOS-L



**Critical Heat Flux On Smooth And Modified Surfaces – Low Pressure Loop**

CHF at 3 MW/m²

- **Scientific objectives**
  - Detailed investigations on Critical Heat Flux (CHF) under reactor typical conditions
  - Measurement data for CFD
- **System parameters**
  - Working fluid: Water
  - System pressure 17 MPa
  - System temperature 360°C
  - System power 2 MW
  - 4 m modular test section (600 kW
- **High resolution instrumentation**

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

## COSMOS-H

**Critical Heat Flux On Smooth And Modified Surfaces – High Pressure Loop**

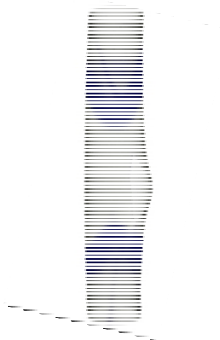
https://www.iket.kit.edu/625.php

# Materials Research: QUENCH-LOCA - Investigations

DBA

- Motivation
  - Cladding embrittlement criterion taking into account oxygen and 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

Unique out-of-pile bundle facility



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.

# Severe Accidents: KIT Experimental Facilities

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Severe Accidents

- In-Vessel and Ex-Vessel Phenomena:
  - Core coolability and debris cooling: QUENCH
  - In-vessel melt retention (IVR): LIVE
  - Fuel Coolant Interaction (FCI): DISCO
  - Molten Corium Concrete Interaction (MCCI): MOCKA
  - Hydrogen Safety: HYKA



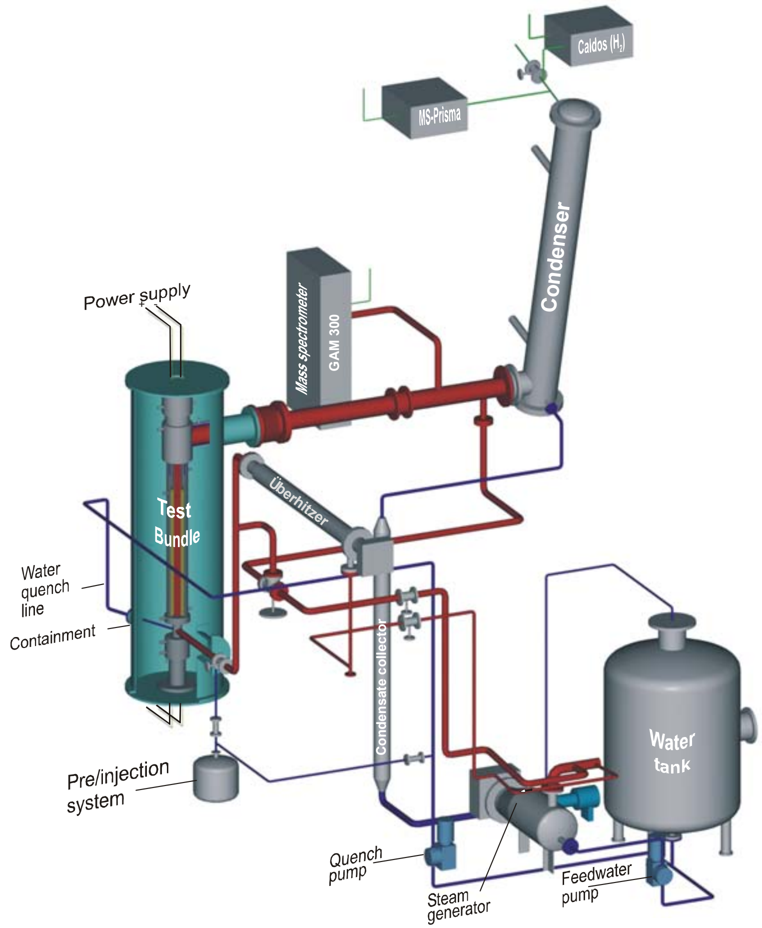

https://www.iket.kit.edu/132.php

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.

Ch. Haas, L. Meyer, Th. Schulenberg; FLOW INSTABILITY AND CRITICAL HEAT FLUX FOR FLOW BOILING OF WATER IN A VERTICAL ANNULUS AT LOW PRESSURE. ASME/JSME 2011, March13-17. Hawaii, USA

# KIT QUENCH Bundle Facility

- Unique out-of-pile bundle facility to investigate reflood of an overheated reactor core
- 21-31 electrically heated fuel rod simulators; T up to >2000°C
- Extensive instrumentation for T, p, flow rates, level, mass spectrometry
- So far, 18 experiments on Severe Accidents performed (1996-today)
  - Influence of pre-oxidation, initial temperature, flooding rate
  - B4C, Ag-In-Cd control rods
  - Air ingress; debris formation
  - Advanced cladding alloys
- 7 DBA LOCA experiments with separately pressurized fuel rods




M. Steinbrück et al., Synopsis and outcome of the Quench experimental program, NED 240 (2010), 1714-1727.

# QUENCH Activities for Accident Tolerant Fuel Claddings

- Participation in OECD-NEA Expert Group on Accident Tolerant Fuels for LWRs (EGATFL), IAEA CRP on Accident Tolerant Fuel Concepts for Light Water Reactors (ACTOF), and EC project IL TROVATORE
- Experiments on high-temperature oxidation of ATF claddings in various prototypical experiments in various scales
  - Small-scale separate-effects tests
  - Single-rod experiments including quench phase
  - Large-scale bundle tests in The QUENCH facility

    FeCrAl test with ORNL on 2017
    SiC under discussion with Westinghouse

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

Inductively heated single-rod test

QUENCH bundle for large-scale experiments

# LIVE: Melt pool behavior in the lower head
## - Coolability and melting of debris beds -

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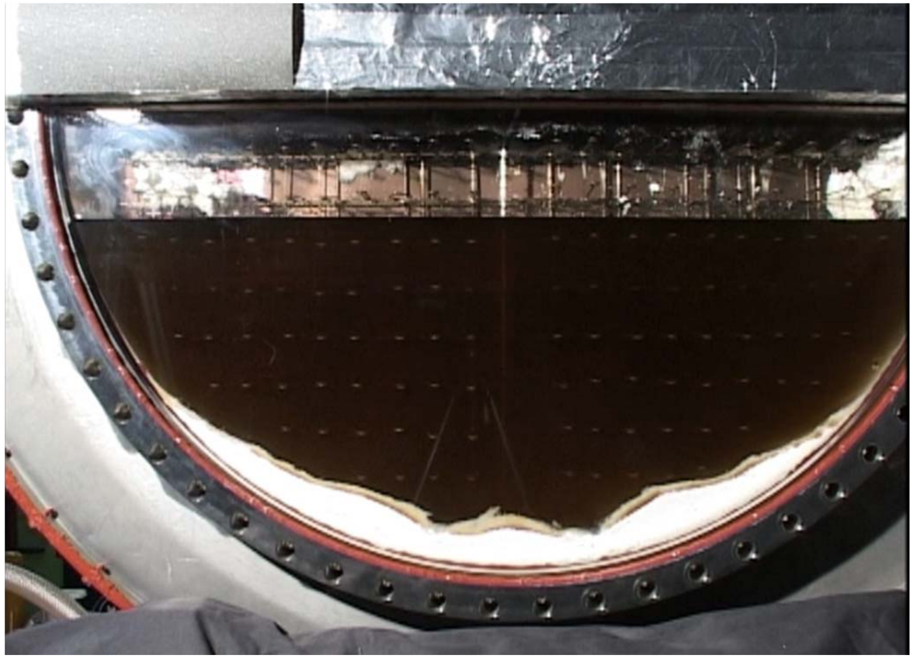


- 1:5 scaled LIVE-3D and LIVE-2D
- Molten salt to simulate corium
- Decay heat simulation by resistance wires
- Different cooling conditions (top, sidewall)
- Melt temperature evolution
- Heat flux profile

- Visualization of debris bed and molten pool behavior
- Transient behavior of heterogeneous debris beds
- Formation and behavior of interfacial crusts in a two-layer pool
- Formation and progression of a molten pool

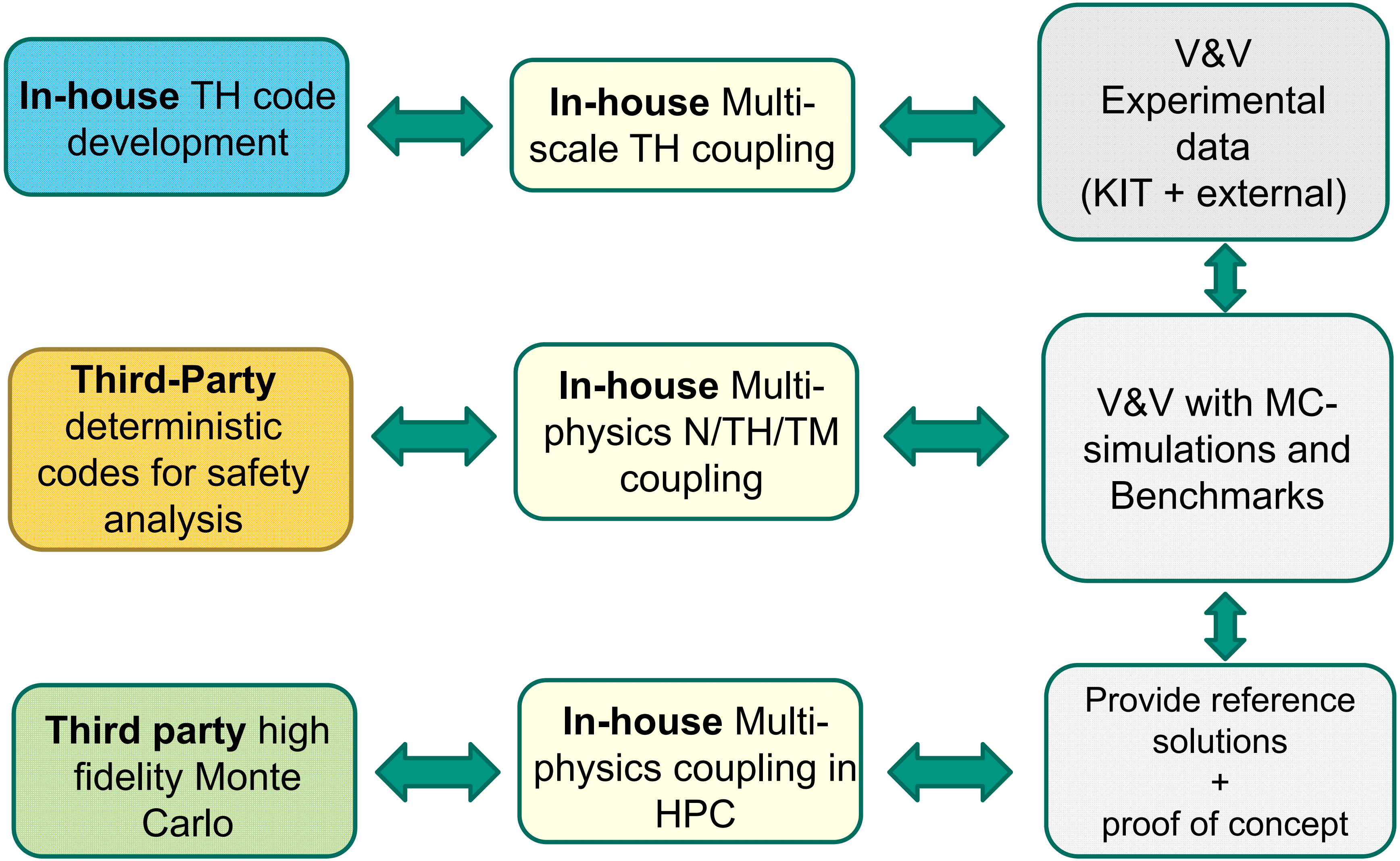
A. Miassoedov et al, Heat Transfer Eng., 2013, DOI: 10.1080/01457632.2013.777247.

# LWR Numerical Investigations for Design Basis Accidents (DBA)

# KIT Strategy for Numerical Simulations

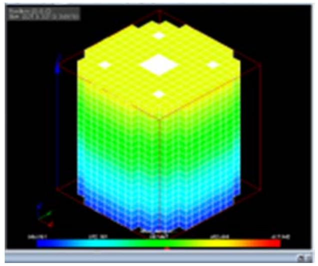
- Strategy:
  - Combination of  innovative research and education and training
  - Combination od in-house code developments and use of foreign codes
- Selection of Key Topics for improved Design, and safety assessment and high operational flexibility
- Integration in national / international activities / programs
- Strategic Partnership with Key Players
- Selected innovative research directions:
  - Advanced physical models and mathematical methods
  - "High-fidelity" simulations and multi-scale procedures
  - Uncertainty quantification
  - Verification, validation  and application & analysis
  - Massive use of High Performance computing (HPC)

# Main Research Safety Topics



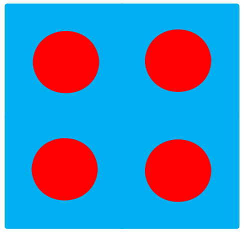
# Thermal Hydraulics: Code Developments & Validation

- **In-house code development**
  - ***Sub-channel code:* SUBCHANFLOW**



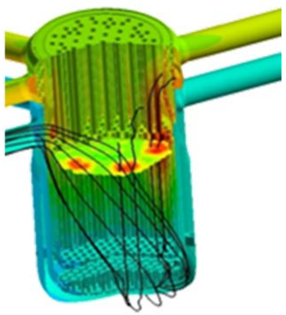
**PWR Core: Square FA**

  - **Porous-media two-phase flow: TwoPorFlow**



**3D Cartesian grid**

- **External codes:**
  - System TH
  - CFD

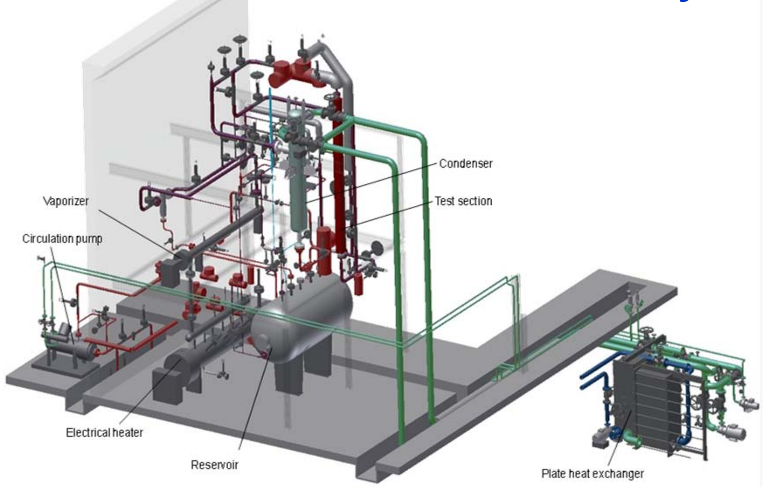


## KIT Test Facilities for Validation:

✓ Counter-current flow in horizontal pipes: **WENKA facility**

✓ Critical heat flux of smooth and rough fuel rods: **COSMOS-L** and **COSMOS-H** water loops

**COSMOS-H Facility**




CAD model COSMOS-H

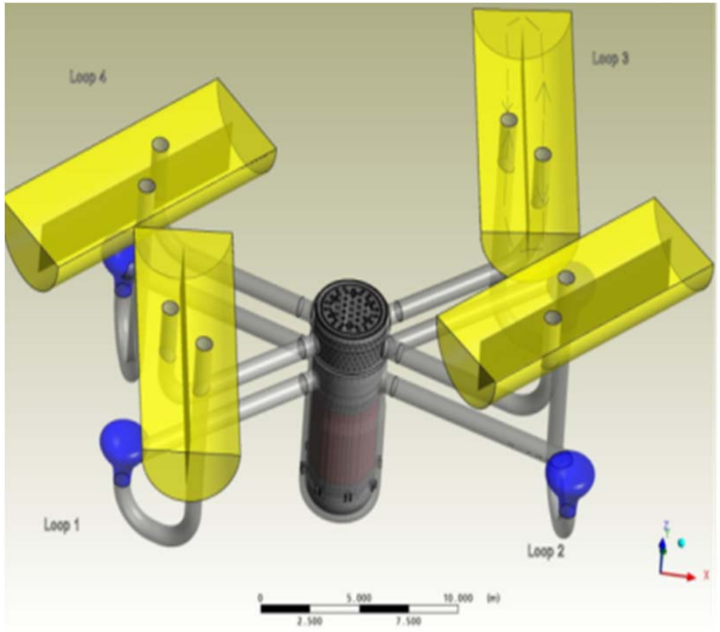
# Multi-Scale Thermal Hydraulics: Developments

- **Current methods (Industry): 1D and coarse 3D TH codes e.g. TRACE, ATHLET, CATHARE**

*Option 1: quasi-3D TH Subchannel Codes*

*Option 2: 3D Porous Media Two-Phase Flow*

*Option 3: Computational Fluid Dynamics (CFD)*




**Nuclear Power Plant (NPP)**

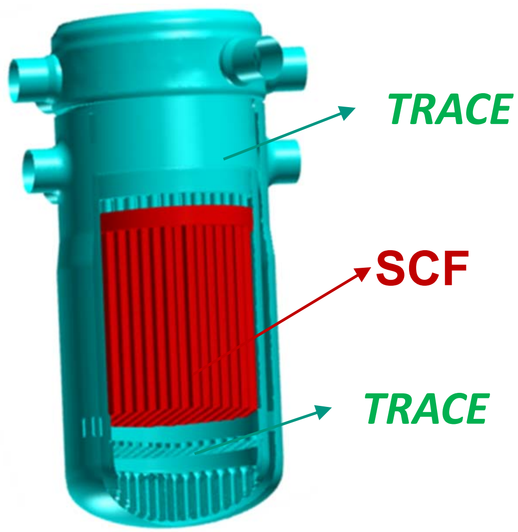
**1.Multi-scale Coupling:**
- NPP: 1D system TH
- Core: subchannel TH

**2. Multi-scale Coupling:**
- NPP: 1D system TH
- Core: Porous media Approach

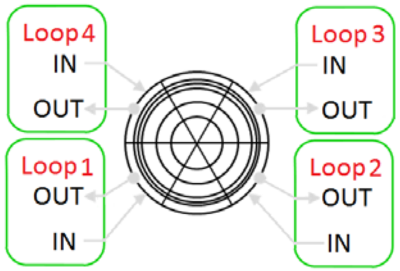
**3. Multi-scale Coupling:**
- NPP: 1D system TH
- RPV and core: CFD

# Multi-Scale TH:
# Coupling of TRACE with SUBCHANFLOW

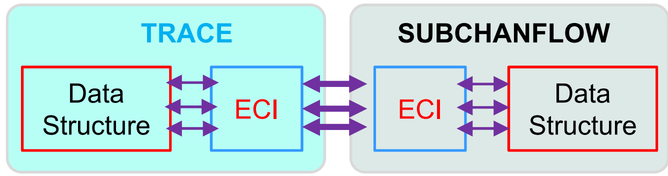
- Approach: TRACE + SCF using ECI (External Coupling Interface: socket communication)
- Validation: VVER-1000 coolant mixing test



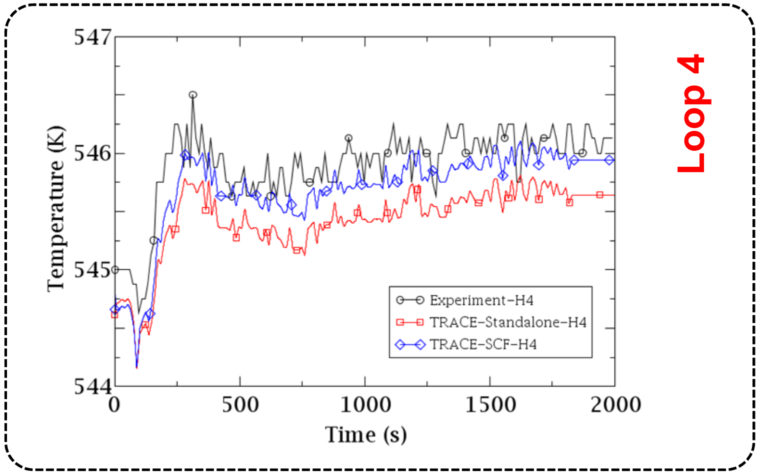

RPV model approach



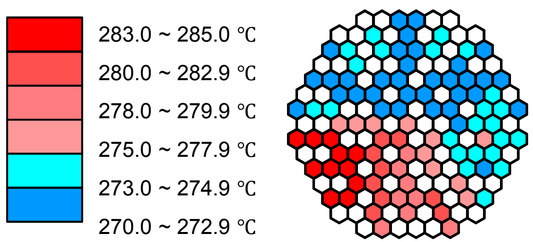

RPV Loops




Coupling scheme




Evolution of Hot leg temperature

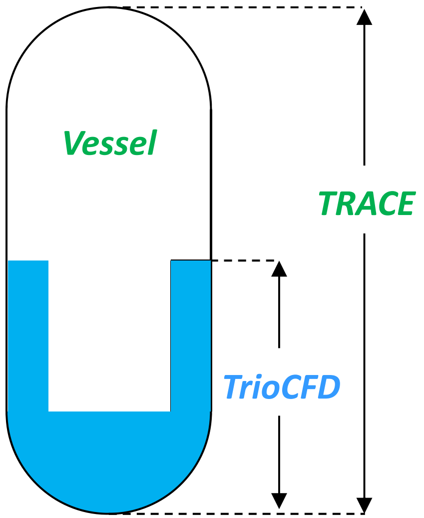



Channel temperature

PhD

# Multi-scale Coupling: TRACE / CFD

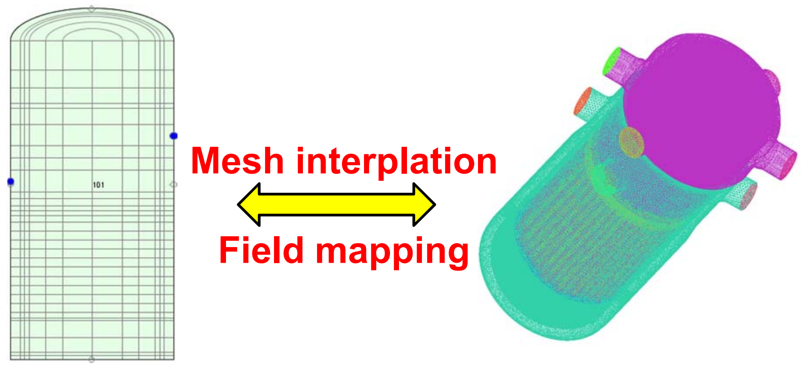
### Computational Domains:




**Overlapping Domain**

- **TrioCFD** calculates the **downcomer** and **lower plenum**.
- **TRACE** simulates the **whole vessel** which also includes the downcomer and lower plenum.
- TRACE will use CFD data to **correct** its physical fields of the overlapping domain.

### Domain interpolation:

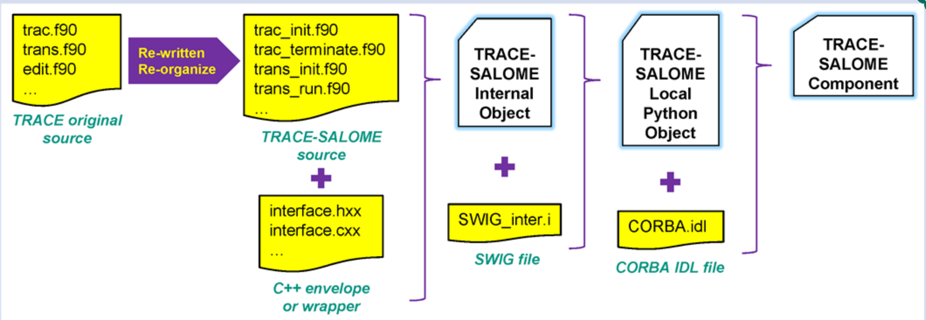



**TRACE corse mesh** **CFD fine mesh**

- The **SALOME** mesh-field interplation library **MEDCoupling** was used for this mapping problem.
- TRACE extracts 2D field which was then traslated to **CFD 2D boundary conditions**.
- CFD get the translated 2D BC and run to extract 3D field which was then traslated to **TRACE 3D field**.
- TRACE use the translated 3D data to **correct** its field in memory.

PhD

# TRACE Implementation in SALOME



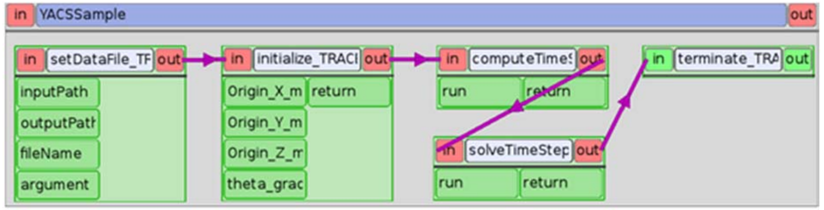

**Steps for the implementation of TRACE:**

1) Modularization of original TRACE source code to meet the functional requirements of SALOME-YACS

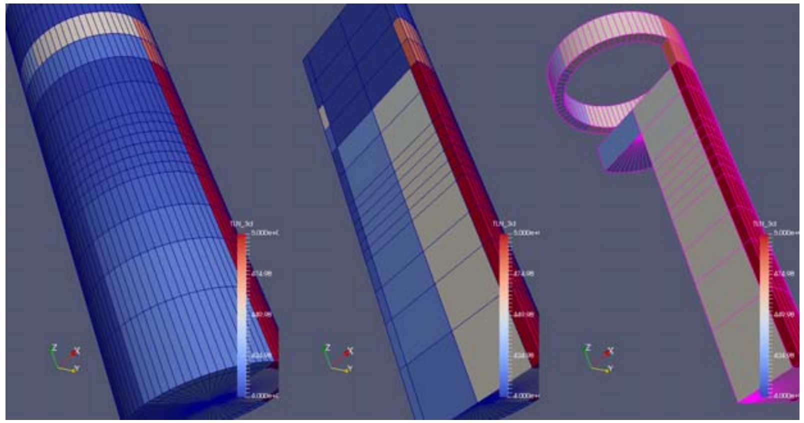
2) Develop a C++ envelope to wrap the lower TRACE Fortran computing engine to form a TRACE-SALOME internal object

3) Develop a SWIG-file to stick the internal object to SALOME-YACS Python layer (TRACE-SALOME local python object)

4) Develop a CORBA-file for communication channels for TRACE module forming the final so called TRACE-SALOME Component




**SALOME: TRACE Calculation chain in YACS**



**VVER RPV: Coolant temperature**

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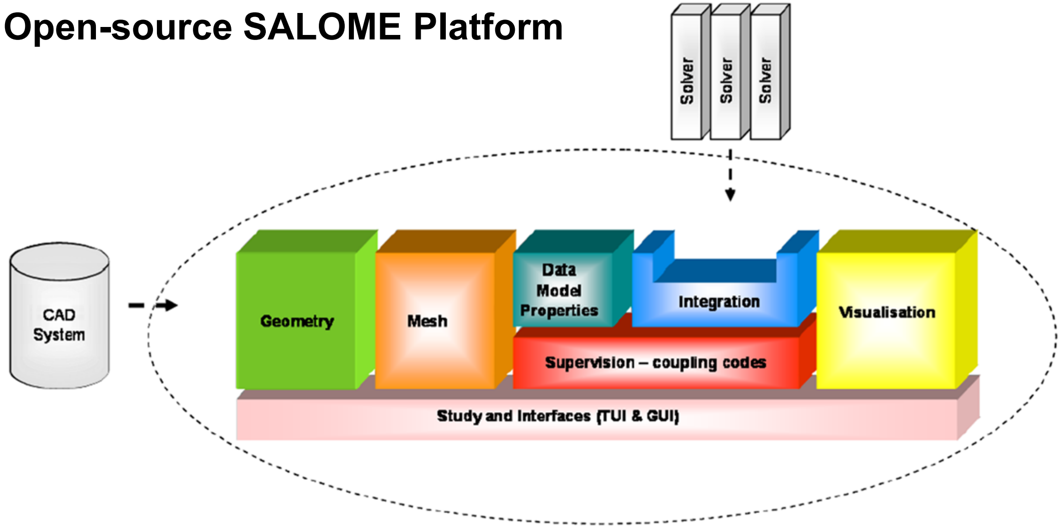
# Code Coupling
# using the EU Simulation platform: NURESIM

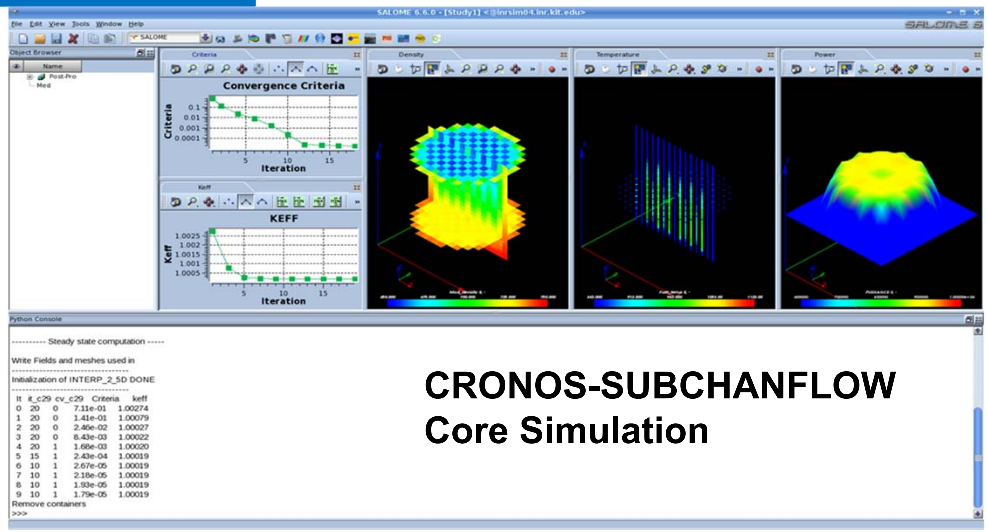
**Open-source SALOME Platform**




- **Multi-physics: N / TH /TM**
- **Multi-scale: macro- and meso-scale**
- **Flexible code coupling**

- **Powerful pre- and post-processor**
- **In-build functions interpolation**

**Neutronic /TH coupling:**

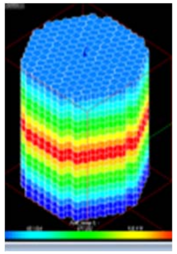



**CRONOS-SUBCHANFLOW**
**Core Simulation**

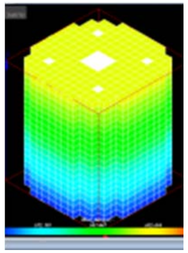
**EU NURESAFE Project (2013-2016)**

# TH Code Integration into SALOME

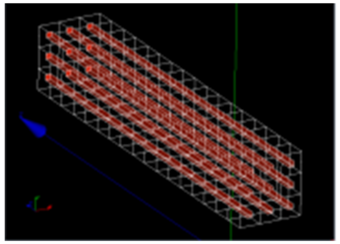
- SUBCHANFLOW: integration in SALOME for coupling with neutronics solver



Core with Hex FA



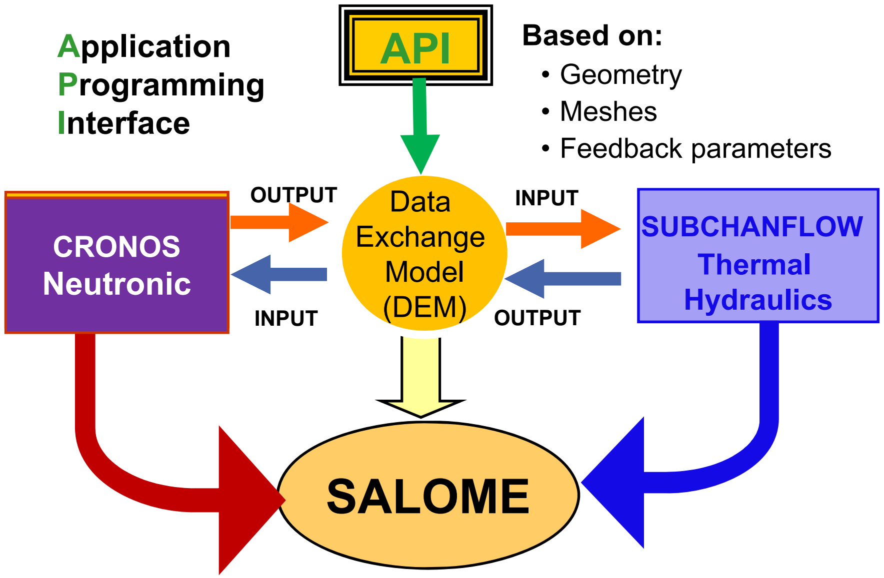
Core with square FA



FA: Pin Level Resolution

- SUBCHANFLOW: Increasing user community (12 institutions): EU, Asia, Latin America, USA

## SCF coupling with Diffusion Solvers




European Simulation Platform NURESIM

EU NURESAFE Project (2013-2016)

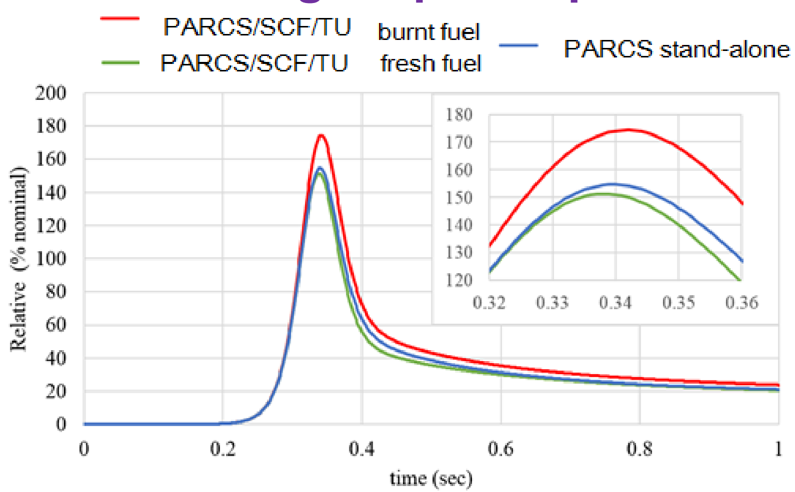
EU H2020 McSAFE (2017- 2020)

# Multi-physics coupling:

## Example 1 → PARCS/SCF/TU: REA Analysis

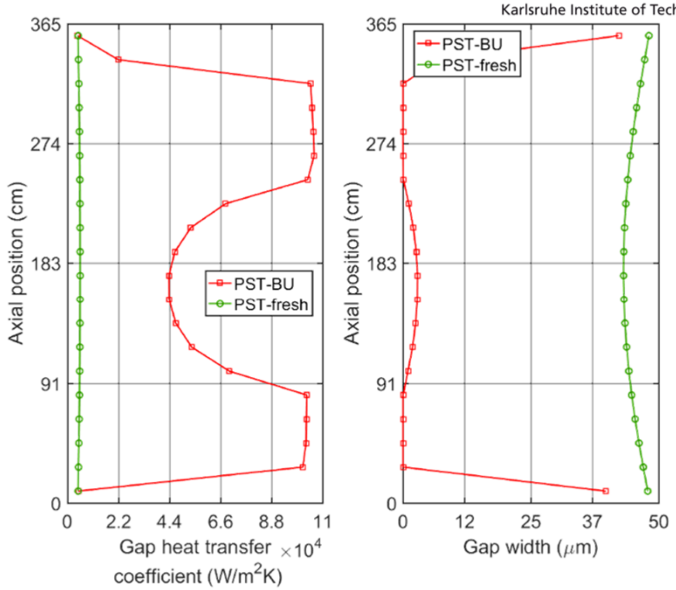
- Core level code + TH + fuel behavior code (TU)
- PWR UOX/MOX core with different irradiated FA
- REA: Ejection of CR in FA-number E5 at HZP

**13 % higher power peak**

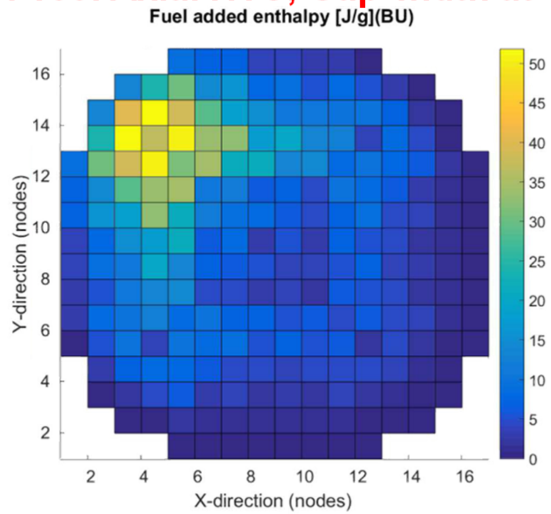



**Power evolution after rod ejection**

More realistic prediction of irradiated fuel behavior due to the thermo-mechanic solver




**FA-160: Axial HTC, Gap-width at 1s**




**Added Fuel Enthalpy at 1 s**

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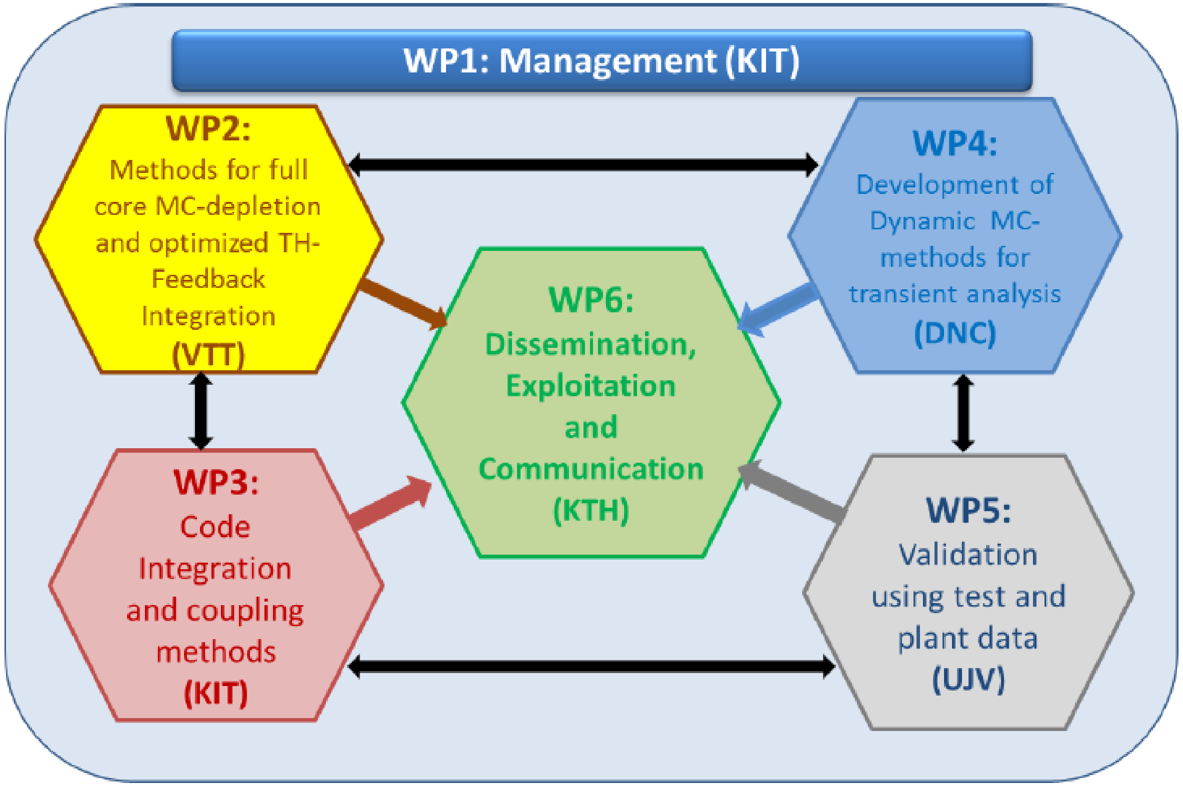
# McSAFE:

## High Performance Monte Carlo Methods for SAFEty Demonstration

Coordinator




**EU H2020 McSAFE (2017- 2020): coordinated by V. Sanchez (KIT)**

# Selected results of McSAFE Project

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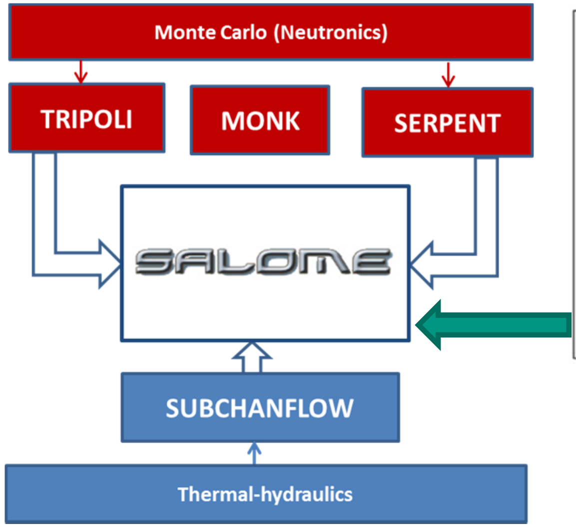
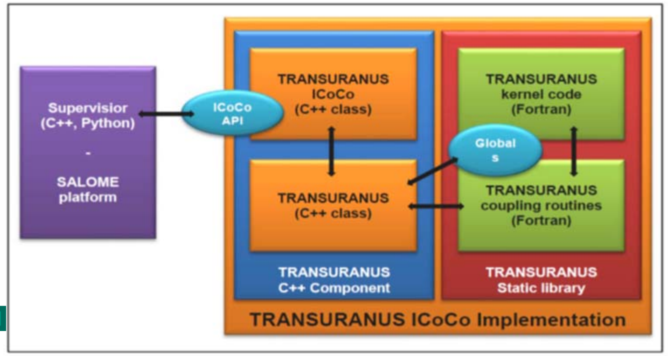


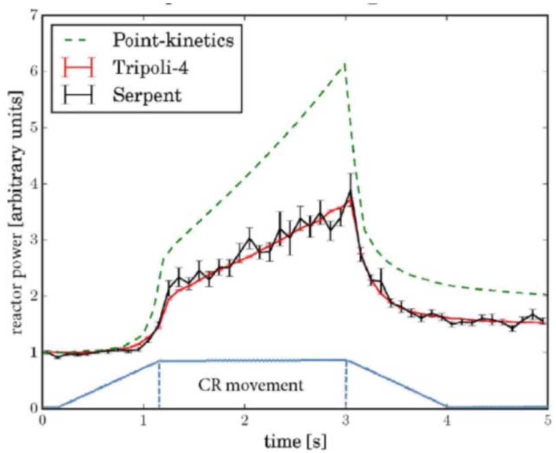




**Pin Thermo-Mechanic: TRANSURANUS**

**Dynamic MC-Codes:**

- **dynTRIPOLI**
- **dynMCNP6**
- **dynSERPENT**

**NURESIM Platform: Integrated McSAFE Codes**




New PhD: Serpent/SCF for VVER reactors

New PhD: SERPENT/TH for research reactors transients

**McSAFE: Dynamic Monte Carlo for Transients**

# LWR Numerical Investigations for Severe Accident

# Motivation

- Fukushima accidents showed necessity for review
  - Re-evaluation of accident analysis methodologies
  - Assessment of NPP safety status
  - Review of SAMG
  - Improvement of numerical simulation tools used for SAM e.g. ASTEC, MELCOR, etc.

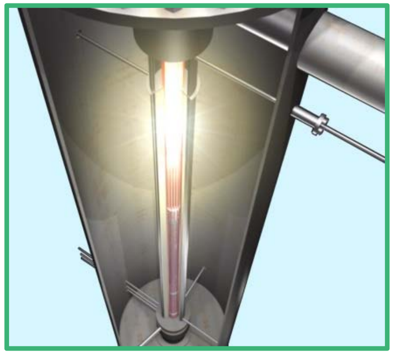
- German activities  in SA embedded in national (WASA-BOSS) and international projects (CESAM, FASNET, etc.)
  - KIT participation of SAM-optimization for BWR within WASA-BOSS project
  - KIT participation n SAM-optimization for PWR within EU CESAM project

- Use of KIT experimental facilities such as QUENCH, LIVE, etc. to validate SA codes

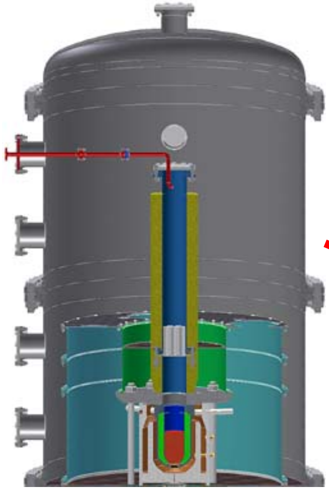
Enhance understanding of SA-Phenomena and the Prediction Capability of SAFETY ANALYSIS TOOLS

# KIT Experimental Facilities: Data for Code Validation

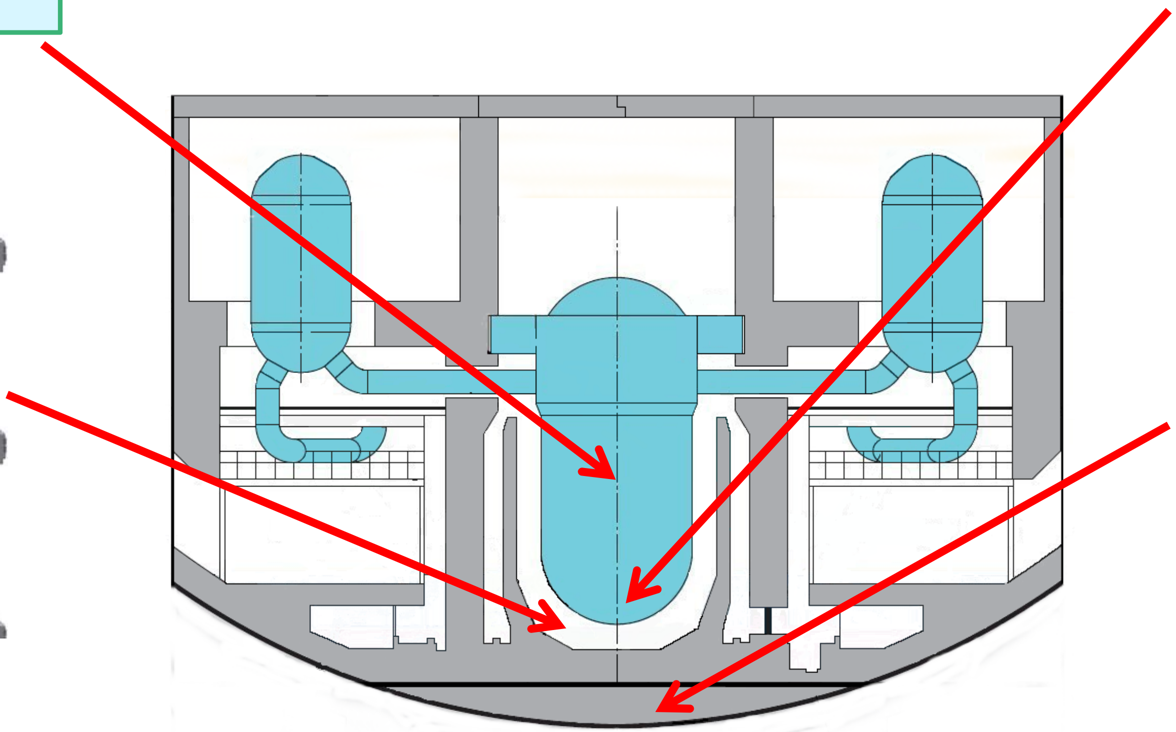
- Core coolability and debris cooling
- In-vessel melt retention (IVR)
- Fuel Coolant Interaction (FCI)
- Molten Corium Concrete Interaction (MCCI)

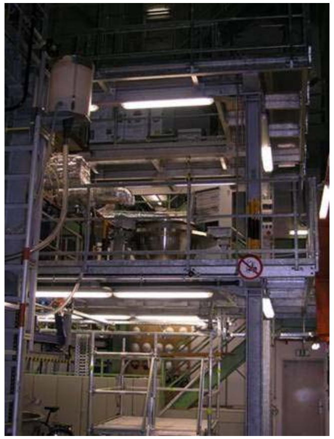


QUENCH



DISCO





LIVE

MOCKA

# Severe Accidents:
# Validation, SAM-applications, Source Term, U&S

- Model developments (ASTEC, MELCOR)
  - BWR-related models
  - Lower plenum models for SA codes

Close collaboration with IRSN, US NRC

- Code extensions by code coupling
  - MELCOR-GASFLOW ➔ Hydrogen in containment
  - ASTEC coupling with JRODOS ➔ source term
  - ASTEC coupling with URANIE ➔ U&S

H2020 FASTNET
HGF
KEK PhD

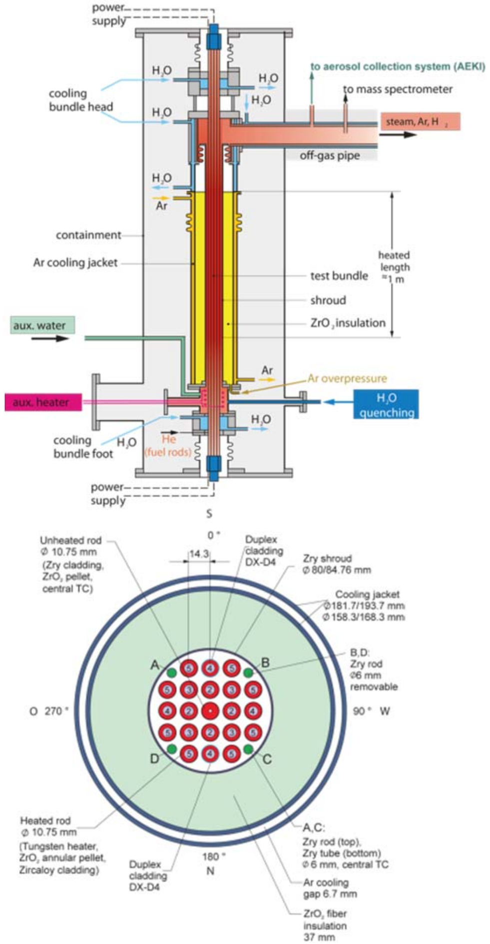
- Code application for accident management
  - VVER-1000 / 1200
  - GE BWR
  - PWR Konvoi

NUGENIA + ASCOM Project

H2020 MUSA Proposal

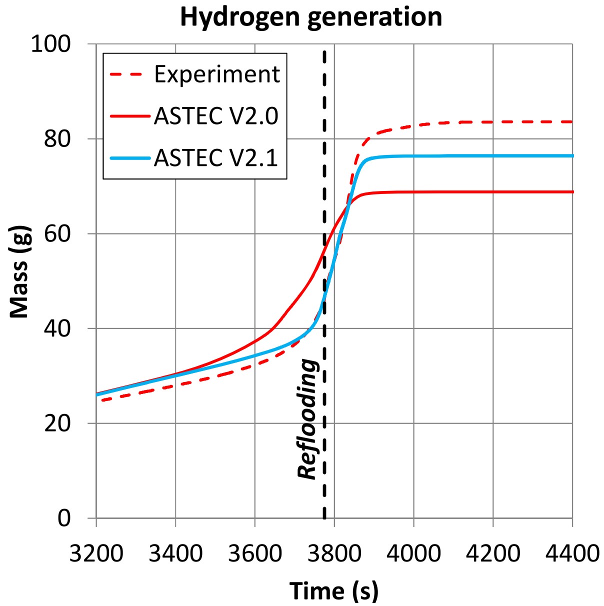
# Severe Accident: Code Validation

Code validation using e.g. KIT experiments CORA, QUENCH, LIVE, etc.




**QUENCH Test Facility:**
**In-Vessel SA-Phenomena**

**ASTEC Validation: Temperature and hydrogen**

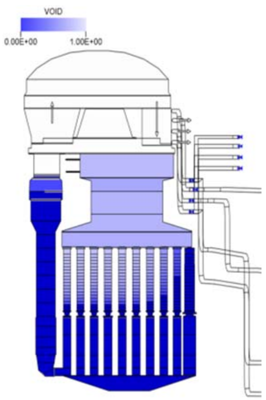



QUENCH-08 test:

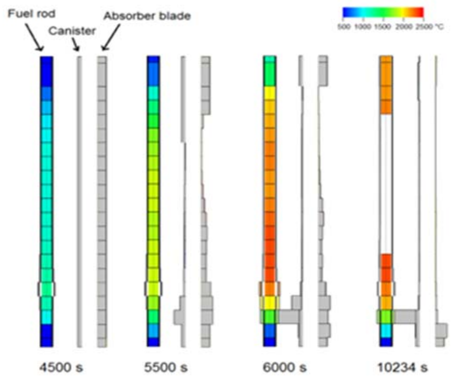
- Similar H2 at end of Experiment: underestimated during reflooding
- Predictions improved with V2.1
  - Radial discretization
  - Radiation upper unheated zone

# Severe Accident: Applications

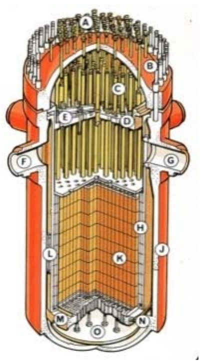
Optimization of accident management for German PWR and BWR



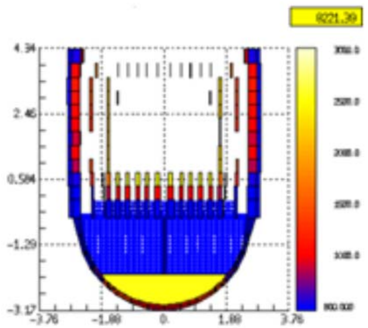

BWR Plant




**ATHLET-CD: Core degradation (10234 s: RPV failure)**



**PWR RPV**



**ASTEC: RPV state before Failure**

**Medium Break LOCA**
(testing purposes)

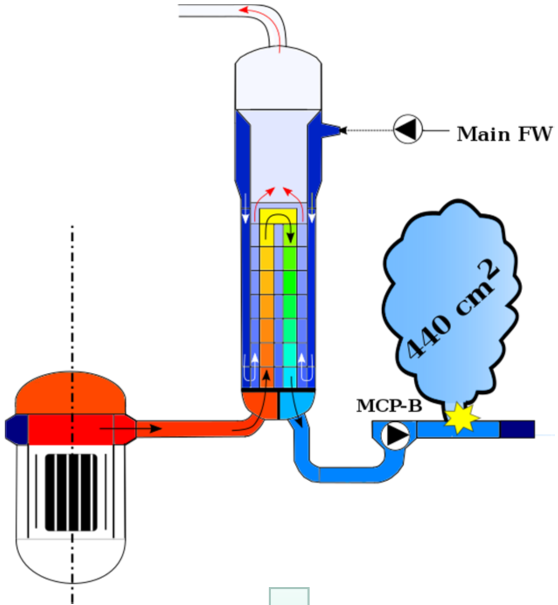
**Small Break LOCA**
(risk core damage)

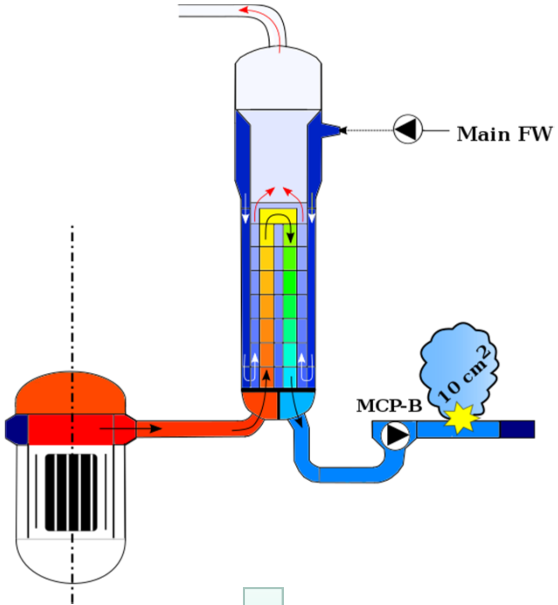
**Station Blackout**
(risk containment damage)

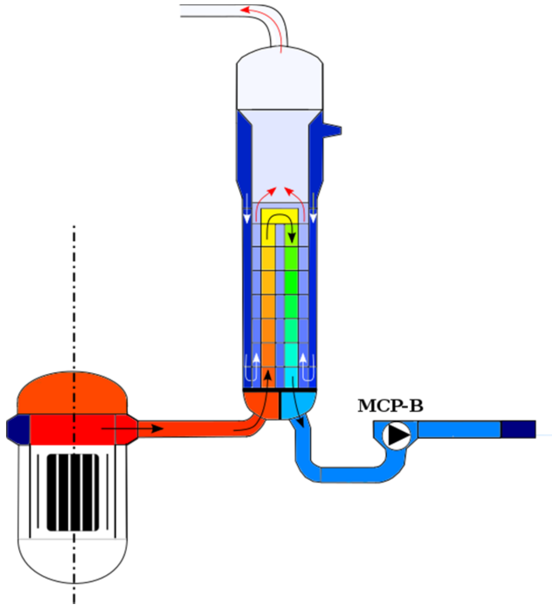
# ASTEC V2.0: Simulation for SAM-Optimization

Karlsruhe Institute of Technology

| **Medium Break LOCA** (testing purposes) | **Small Break LOCA** (risk core damage) | **Station Blackout** (risk containment damage) |
|---|---|---|




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.

I. Gómez García-Toraño, et. al (2017). Analysis of primary bleed and feed procedures during selected SBLOCA sequences along with Station Blackout in a generic Konvoi PWR using ASTECV2.0. Annals of Nuclear Energy. Submitted.

**Hypotheses:**

- No surge line failure
- No 100 K/h cool down
- Passive seals MCPs
- No Temp-induced SGTR

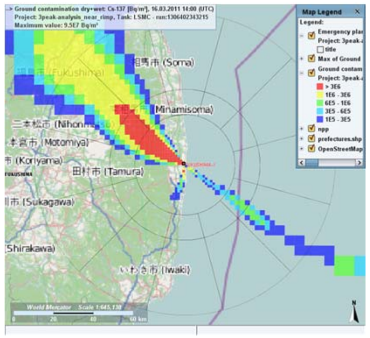
# KIT JRODOS: Emergency Management

Karlsruhe Institute of Technology

- Real-time on-line decision support system for nuclear and radiological incidents
  - Considering releases into water and the atmosphere
  - Determining contamination levels in the urban and agricultural environment and doses to the public

**https://resy5.iket.kit.edu/**

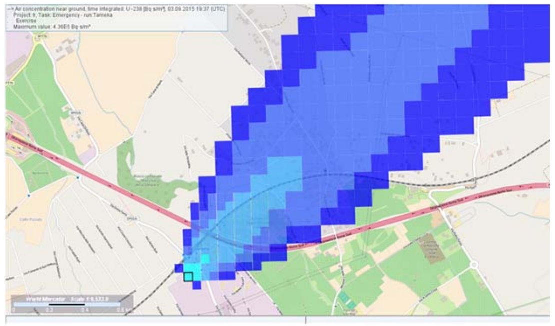
### Emergency
- Adapted to Japan in the first week of the release
- Numerical weather data from NOMADS
- Needs rad- source terms s input




### Preparedness
- > 5000 simulations,
  - 3 source terms
  - 3 sites
  - 1 year
- New pre-planning zones

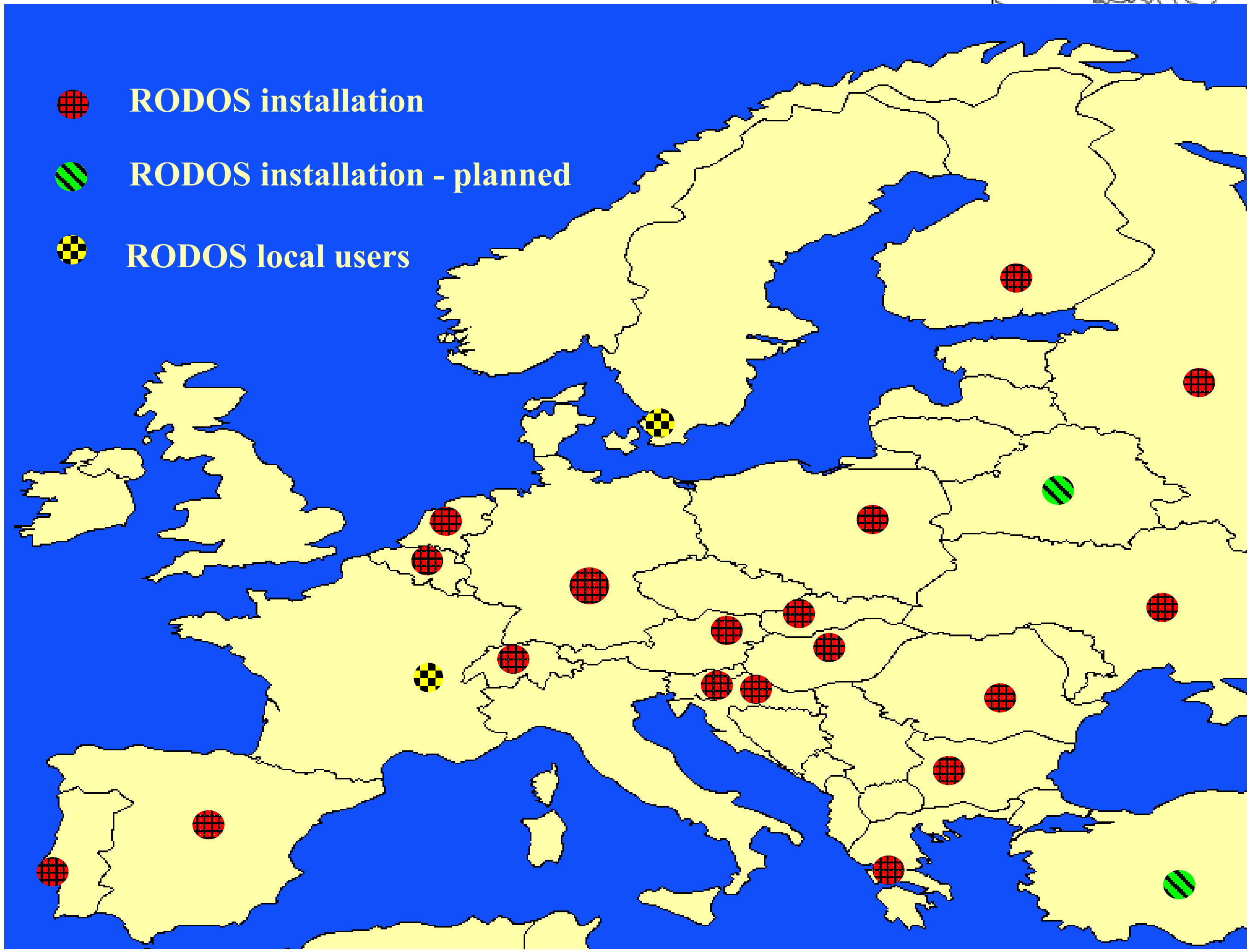
| Old | New |
|---|---|
| **Central zone up to 2 km distance** | **Central zone up to 5 km distance** |
| Middle zone up to **10** km distance | Middle zone up to **20** km distance |
| Outer zone up to **25** km distance | Outer zone up to **100** km distance |
| Far zone up to **100** km distance | **Whole Germany** |

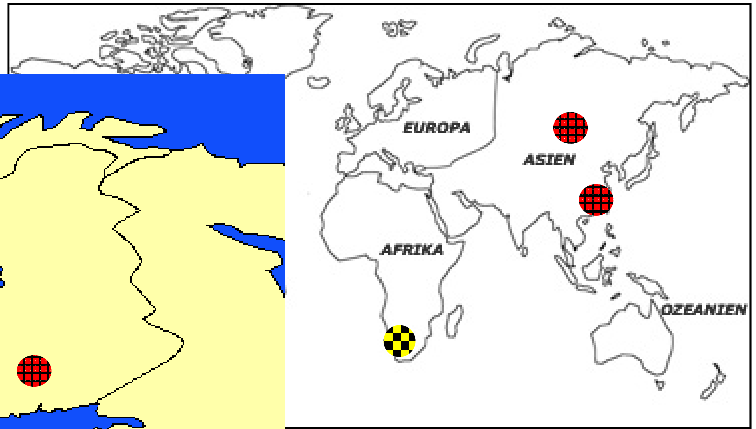
### Exercises
- NPP accidents and Radiological Dispersal Device incidents
- Figure: Exercise in Frascati, Italy.



*Ievdin, I.,Trybushny, D., Zheleznyak, M. & Raskob, W. (2010). RODOS re-engineering: aims and implementation details. Radioprotection 45(5).*

# KIT JRODOS: Overview of World-Wide Users (2017)



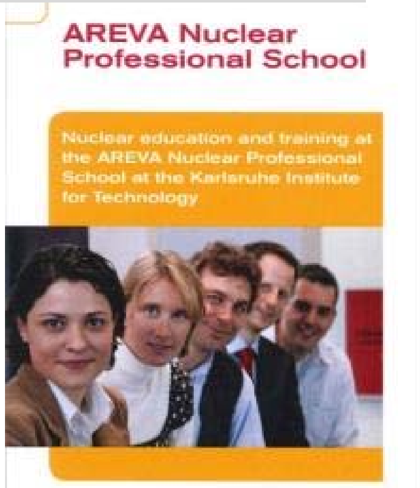

2017 Installation in China completed

2018 – 2020 Installation in ASEAN countries envisaged

# KIT Education & Training Activities

www.fps.kit.edu

- University (different faculties)
  - Nuclear technology lectures
  - PhD students
- Cooperation within ENEN
  (European Nuclear Education Network):
  - ANNETTE
  - ENEN+
- FRAMATOME Nuclear Professional School at KIT
  (former AREVA)




www.fjohss.eu

- Frederic Joliot Otto Hahn Summer School
  (together with CEA/France)
  - Since 25 years
- Training Centre for Technology and Environment (FTU)


**Knowledge Dissemination in Reactor Safety**

www.ftu.kit.edu