Reactor Safety Investigations at KIT with the HGF NUSAFE Program

V. Sanchez, W. Tromm and R. Stieglitz
Victor.sanchez@kit.edu, walter.tromm@kit.edu, robert.stieglitz@kit.edu

Outline

- KIT Reactor safety program within NUSAFE
- Experimental facilities for LWR
- Experimental facilities for innovative systems
- Numerical simulations for LWR
- Summary

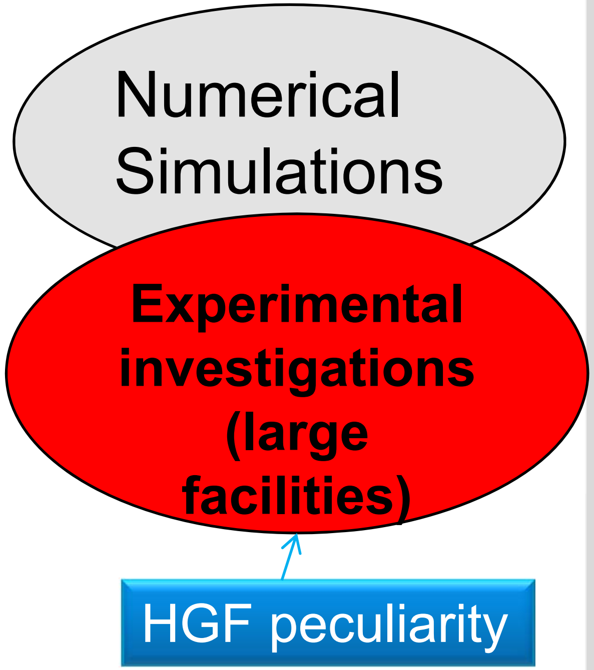
HGF NUSAFE Program at KIT

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
  - Reactor Dynamics and Accident analysis
  - Thermal hydraulics
- Subtopic 2.2: Beyond Design Basis Accidents and Emergency Management
  - Severe Accident Analysis
  - Emergency Management



KIT Experimental investigations for Reactor Safety

Karlsruhe Institute of Technology

- **Design basis accident research**
  - LWR thermal hydraulics and safety:
    - COSMOS-L (CHF water) and COSMOS-H (CHF water)
  - 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
    - DISCO (Corium dispersion out of reactor pit into containment)
    - MOCKA (MCCI: molten corium concrete interactions)
  - LWR Containment phenomena
    - Hydrogen Safety Test Centre (2 pressure vessels (A1 and A3, h distribution, h combustion in large range of geometrical and energetic scales)
    - Detonation Tube (H detonation tests)
    - Flow test chamber (vented combustion and detonation, shock waves)

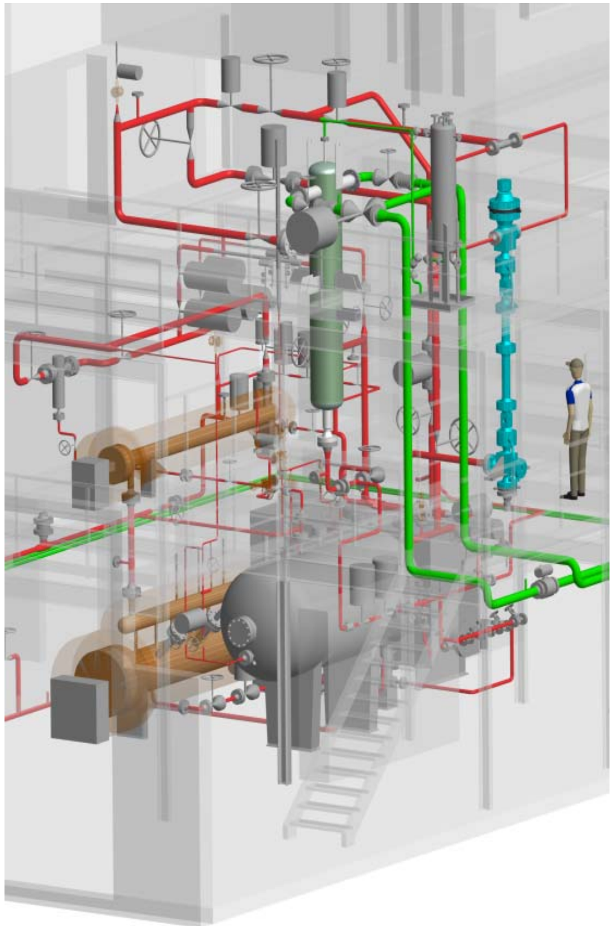
Experimental Investigations for LWR DBA and Severe Accidents

COSMOS-H Facility

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

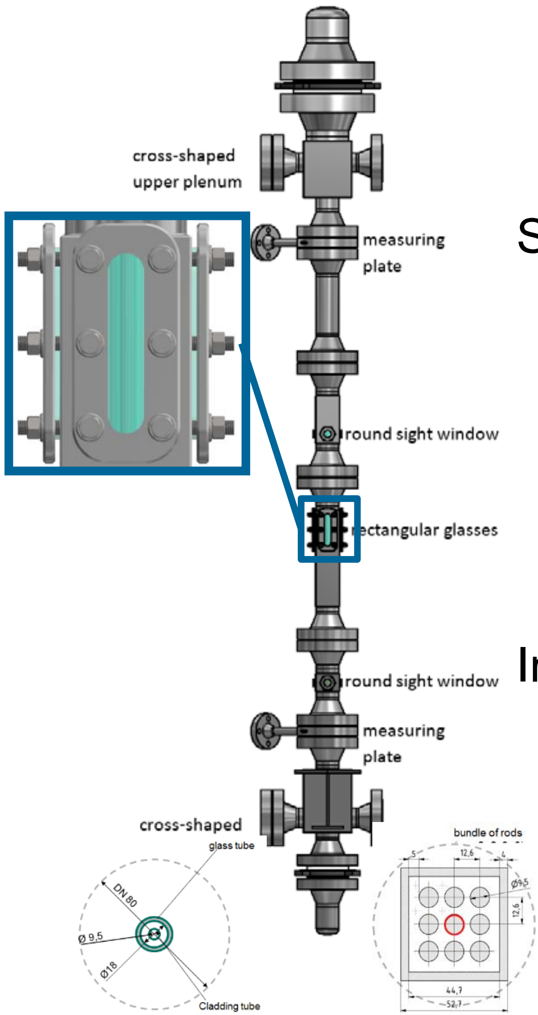
Karlsruhe Institute of Technology

Facility



Commissioning phase

Test section



Scientific objectives

- Detailed investigations on Critical Heat Flux (CHF) under reactor typical conditions
- Provide data for code validation

System parameters

- Working fluid: demineralized water
- System pressure: 17 MPa
- System temperature: 360°C
- Power: 2 MW
- Test section length: 4 m (modular, 600 kW)

Instrumentation

- 246 Sensors
- Temperature, void, pressure, velocity, mass flow, power, liquid level
- 8 glass windows
- LDA, PIV, shadowgraphie

QUENCH Tests Program

- Objective:
  - Reflooding of overheated rod bundle
- Facility description:
  - bundle facility 21-31 electrically heated fuel rod simulators
  - Bundle overheating up to >2000°C
  - Extensive instrumentation for T, p, flow rates, level, mass spectrometry
- Test program:17 tests (since 1996-today)
  - Influence of pre-oxidation, initial temperature, flooding rate
  - B_4C, Ag-In-Cd control rods
  - Air ingress
  - Debris formation
  - Advanced cladding alloys
- LOCA experiments: 7
  - separately pressurized fuel rods (55 bar)

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

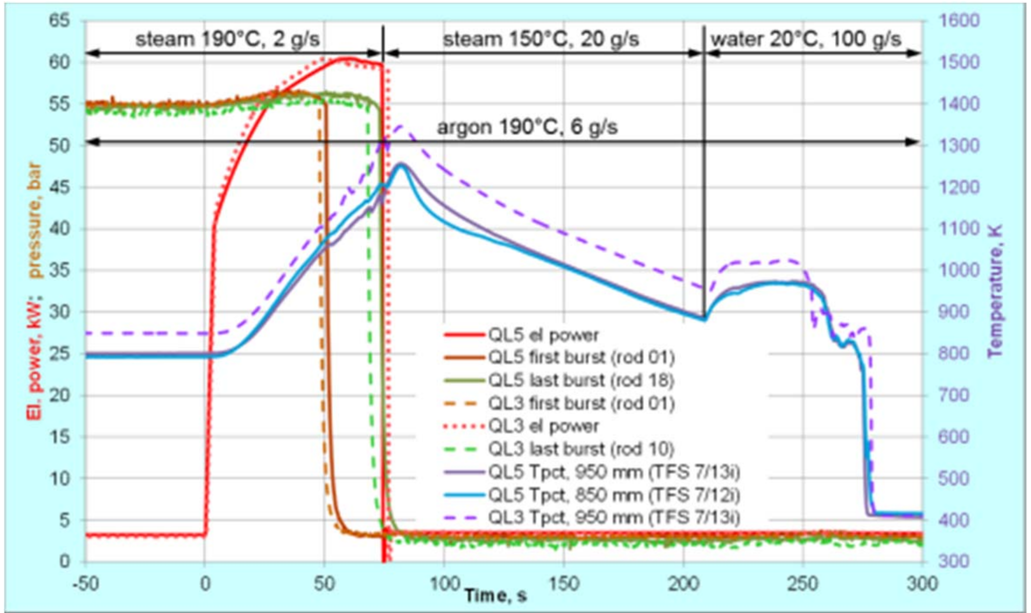
Main goal: contribute to understand physics and provide data for code validation for PWR, VVER, BWR

QUENCH-LOCA (L5: 17.2.2016)

23th QUENCH Workshop
17-19. October 2017

- Peculiarities:
  - pre-hydrogenated Zirlo^{TM} cladding
- Post-test examinations:
  - mechanical testing, metallography, neutron radiography and tomography,
  - micro hardness measurements, and
  - X-ray Diffraction (XRD), Transmission Electron Microscopy (TEM)

QUENCH-L5:test conduct



rod #1:
burst opening

rod #1:
neutron
tomography

QUENCH Investigations: Accident Tolerant Fuel Claddings

- Participation on
  - 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-tem. oxidation of ATF claddings in various prototypical experimental 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

Inductively heated single-rod test

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

QUENCH bundle for large-scale tests

Selected Experimental Facilities for Innovative Systems (GEN-IV)

KIT Tests on Liquid Metal Science:

KIT Karlsruhe Institute of Technology

- **Goals:**
  - Develop measurement techniques for liquid metal flows
  - Investigate the compatibility of coolants structural materials
  - Investigate material corrosion
- **Coolants:** Lead, Lead-Bismuth, Indium-Gallium-Tin, Sodium, Sodium-Potassium, Tin
- **KIT Experience:**
  - Liquid metal technology: pumps, heat exchangers, instrumentation, operation and control safety
  - > 30 years, leading partner in German and European LM research

SEARCH MARISA HELMHOLTZ ASSOCIATION

MAXSIMA MYRTE LIMTECH Alliance

HORIZON 2020 LE PROGRAMME DE RECHERCHE ET D'INNOVATION DE L'UNION EUROPÉENNE

SESAME

Combination of Experiments and Simulation

Test Facilities of Different Scales: Laboratory Scale…

COSTA: COrrosion test stand for STagnant liquid lead Alloys

- Operative since 1997
- Pb, Pb-Bi, Sn
- Equipped with O2-control
- Influence of protection layers and coatings on corrosion

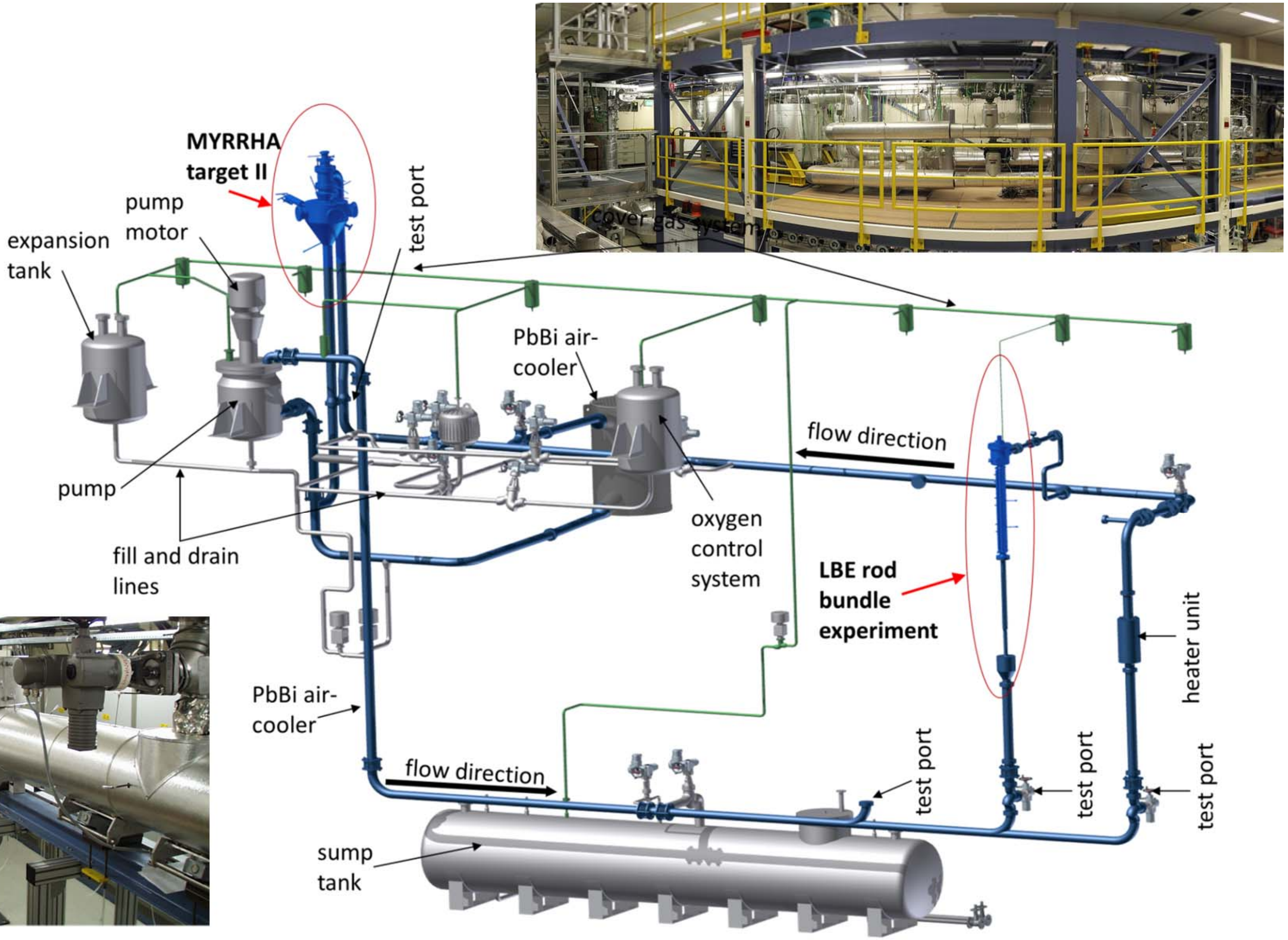
CRISLA: Creep-to-Rupture In Stagnant Lead Alloys

- Operative since 2007
- Pb or PbBi at max. 650°C
- Equipped with O_2-control
- Impact of liquid-metal environment on creep performance

… to Prototype Dimensions, e.g. THEADES Facility

Parameters:

- **T-range: 190°C - 450°C**
- **G: 42 m³/h**
- **P: 10 bar**
- **V: 4 m³ / 44 t**
- **Power: 1 MWth**

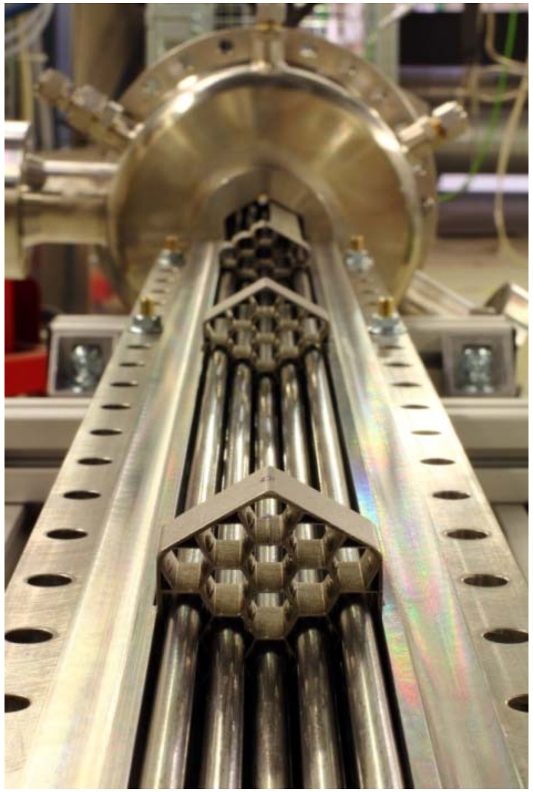


LBE THESYS2 Loop at KALLA:
Fundamental Research for LM Heat Transfer in Rod Bundles

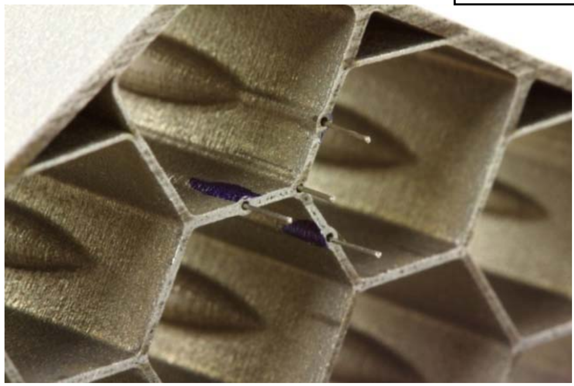
Karlsruhe Institute of Technology

THINS

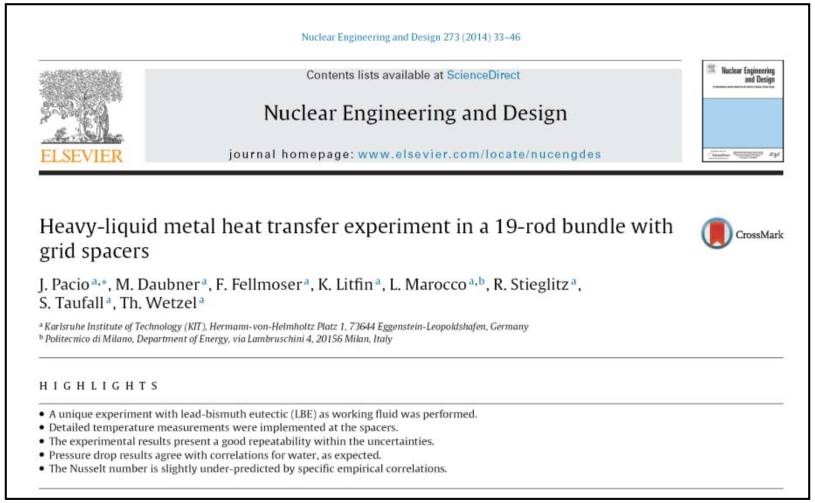
SESAME



19 Pins Bundle



Spacer grids



Nuclear Engineering and Design 273 (2014) 33–46

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Heavy-liquid metal heat transfer experiment in a 19-rod bundle with grid spacers

J. Pacio[a,*], M. Daubner[a], F. Fellmoser[a], K. Litfin[a], L. Marocco[a,b], R. Stieglitz[a], S. Taufall[a], Th. Wetzel[a]

[a] Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz Platz 1, 73644 Eggenstein-Leopoldshafen, Germany
[b] Politecnico di Milano, Department of Energy, via Lambruschini 4, 20156 Milan, Italy

HIGHLIGHTS

- A unique experiment with lead-bismuth eutectic (LBE) as working fluid was performed.
- Detailed temperature measurements were implemented at the spacers.
- The experimental results present a good repeatability within the uncertainties.
- Pressure drop results agree with correlations for water, as expected.
- The Nusselt number is slightly under-predicted by specific empirical correlations.

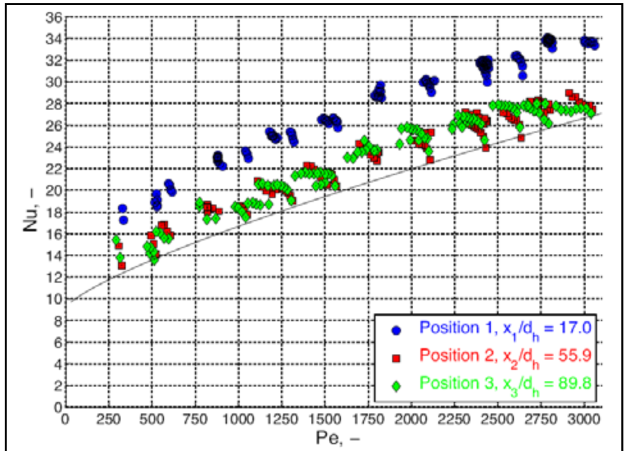


Fig. 11. Experimental Nu and Pe at three axial positions. The solid line represents the empirical correlation given by Eq. (B.5).

- Understand key phenomena
- Provide data for code validation

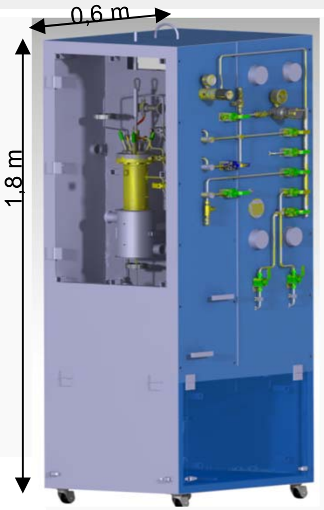
KASOLA & HAC: Experiments with Sodium

HAC: Helmholtz AMTEC Center)

Goals:

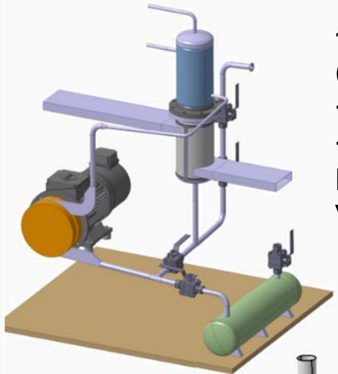
Basic physics (Electro-chemistry)	System level (Materials)	Medium Scale / Demonstrator (Systems)

AMTEC test facility: ATEFA (→ 900°C)

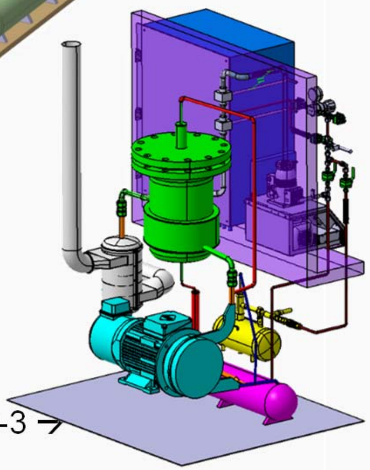


← DITEFA (GaInSn) .

„Energy“ -Materials: SOLTEC-1 & 2



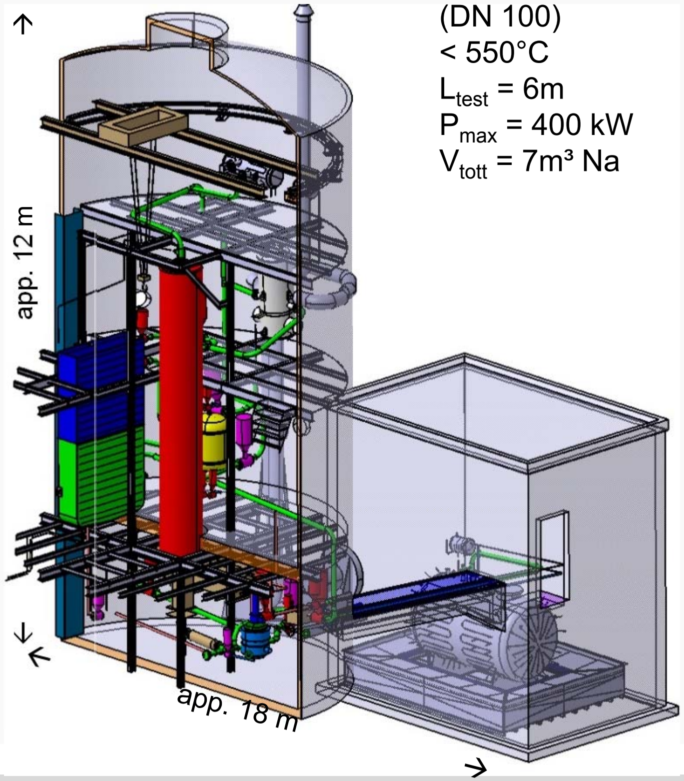
~300 l/h
(DN 20/16)
< 750°C (S1+S2)
< 1000°C (S3)
P_{max} = 10 kW
V_{tott} = 11 l Na



SOLTEC-3 →

System behaviour: KASOLA facility

~150 m³/h
(DN 100)
< 550°C
L_{test} = 6m
P_{max} = 400 kW
V_{tott} = 7m³ Na

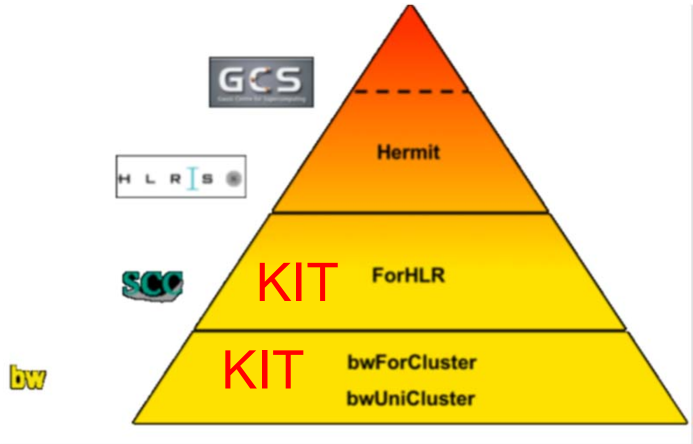


KIT Numerical Investigations

KIT Strategy for Numerical Simulations

- **Strategy: combination of**
  - innovative research and education and training and
  - in-house code developments and use of external codes
- **Selection of KEY TOPICS for improved design and safety assessment**
- **Integration in national / international activities / programs**
- **Strategic Partnership with Key Players**
- **Selected innovative research directions:**
  - Advanced physical models and mathematical methods
  - "High-fidelity" multi-physics and multi-scale simulations
  - Uncertainty quantification
  - Verification, validation and application & analysis
  - Massive use of High Performance computing (HPC)

- **HPC computer Centers in state Baden Württemberg**



KIT: Research High Performance Computer ForHLR II (> hundred thousands processors)

KIT Numerical Simulation for Design Basis Accidents

Karlsruhe Institute of Technology

Thermal Hydraulics

- ANSYS-CFX, OpenFOAM
- **Own development:**
  - **SUBCHANFLOW, TWOPORFLOW**
- RELAP5, TRACE
- TRACE/SUBCHANFLOW (ECI)

Neutron Physics and Dynamics

- Lattice pyhsics: SCALE6, SERPENT
- **Own development: High fidelity pbp**
  - **MCNP5/SCF, SERPENT/SCF**
- Reactor dynamics
  - PARCS, DYN3D-MG

Multi-physics Simulations

- Nodal solutions: TRACE/PARCS, TRACE/DYN3D
- High fidelity solutions: **DYNSUB5 (sp3 and subchannel TH)**
- N/TH/ TM: **PARCS/SCF/TRANSURANUS**
- NURESIM Platform:
  - **SCF**/DYN3D, **SCF**/COBAYA, **SCF**/CRONOS

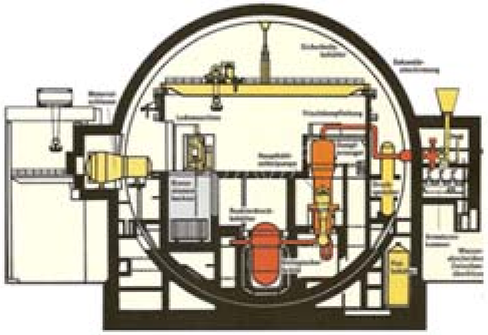
LWR

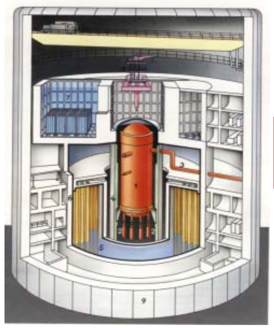
GEN-IV

Application of Numerical Tools:

Gen- II LWR:

PWR Konvoi

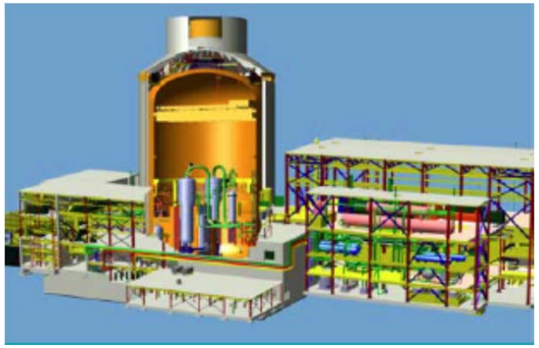




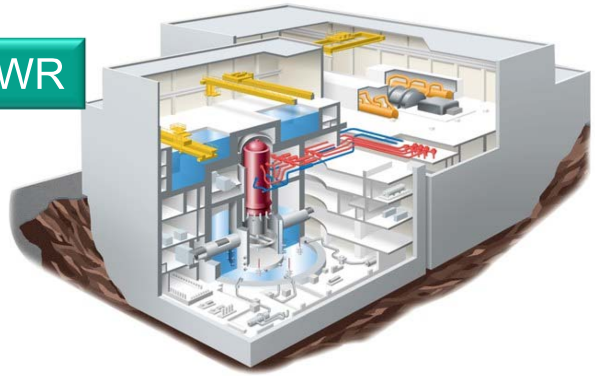
BWR Type-72

Gen- III LWR:

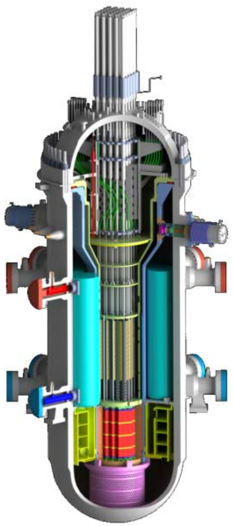
AP-1000



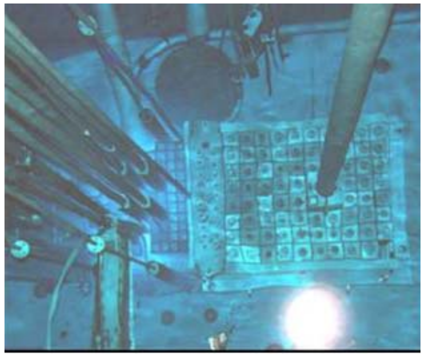
ABWR



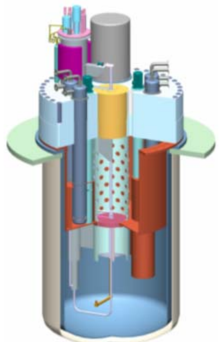
Gen-IV:



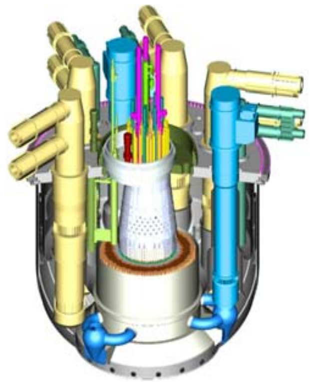
SMR SMART



MTR
Research Reactors

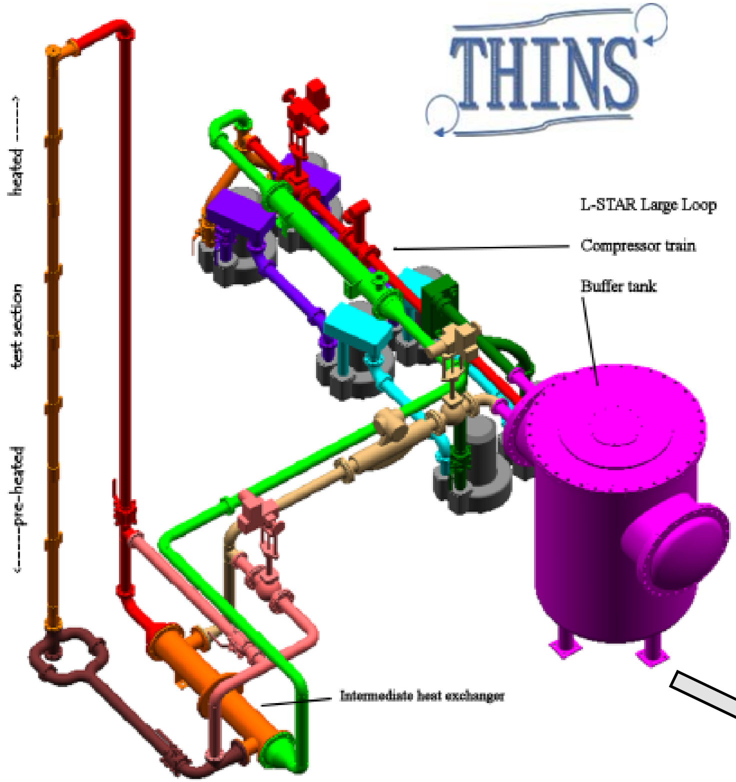


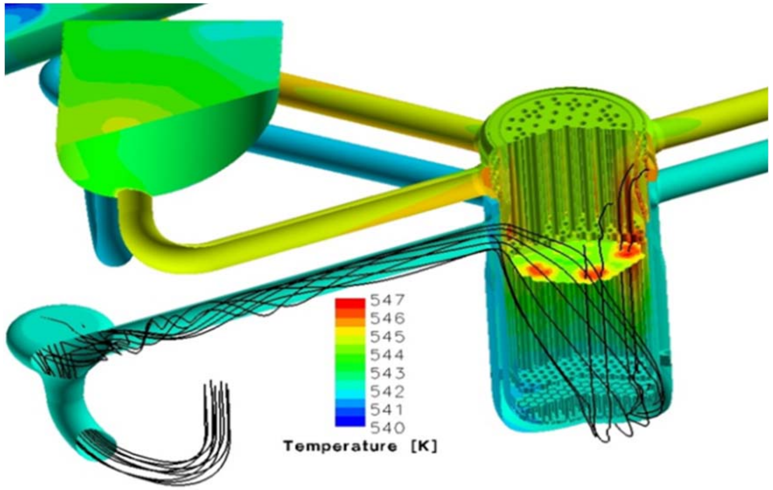
LFR (ADS)



SFR

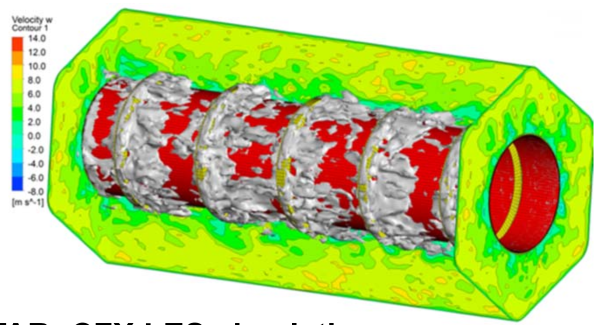
Thermal Hydraulics: Code Validation and CFD Simulations





KIT CFX Model of integral VVER-1000

- **L-START Helium Loop**
  - Improvement of heat transfer by surface roughness
  - Qualification and improvement of turbulence models
- **Provide data for code validation**

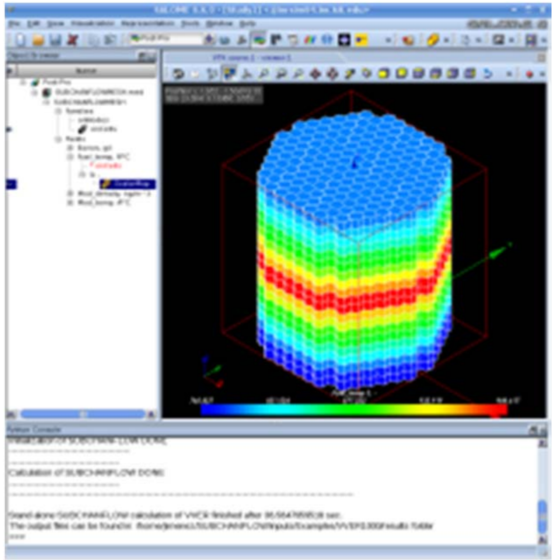


L-STAR: CFX LES simulation: Instantaneous velocity distribution

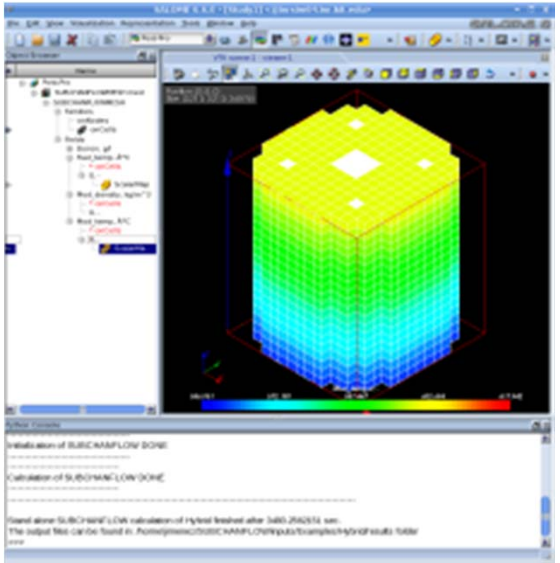
M. Böttcher

SUBCHANFLOW:
Fast Running Code for LWR and Gen-IV Reactors

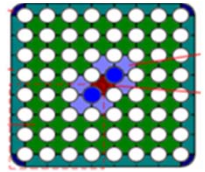
- **Coupling with MC-codes SERPENT, MCNP5 and TRACE, PARCS and TRANSURANUS**

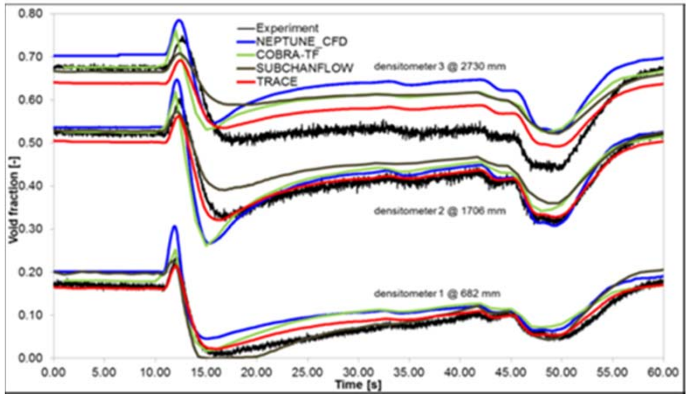


VVER Core: Hexagonal FA

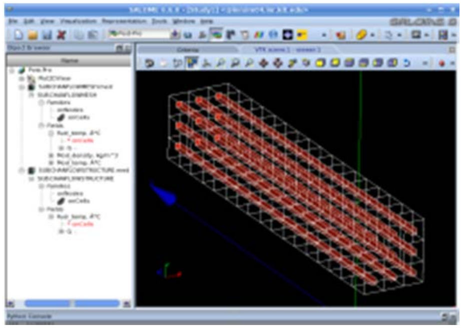


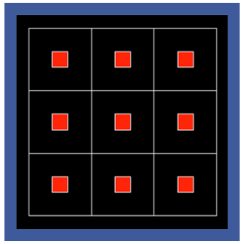
PWR Core: Square FA





SUBCHANFLOW Validation: BWR NUPEC





FA: Pin Level Resolution

KIT
Cooperation based on KIT Code SUBCHANFLOW Users

Karlsruhe Institute of Technology

SUBCHANFLOW KIT TH Code

HZDR Dresden
- Simulation of single and two phase flow tests

RWTH Aachen
- INBK: Simulation of transmutation system (AGATE)

FZ Jülich
- IEK Reactor Safety SMR

National

Goals of cooperation:
- Develop high fidelity simulations based on multi-physics coupling with
  - Neutronic solvers (stochastic and deterministic)
  - Thermo-mechanic solvers
- International Benchmarks e.g. BFBT, PSBT
- Code improvement and validation:
  - (Internships, Bachelor, MSc, PhD)

EU JRC IE Petten
- Gen-IV reactors

UPM/Spain
- Coupling with COBAYA3

RC Demokritos / Greece
- Coupling with OpenMC

DNC / Netherland
- Coupling with Monte Carlo Codes

CIEMAT/ Spain
- Coupling with MCNPX

Uni Gadjah Mada/Indonesia
- SMR applications

CNEA/ Argentine
- SMR applications

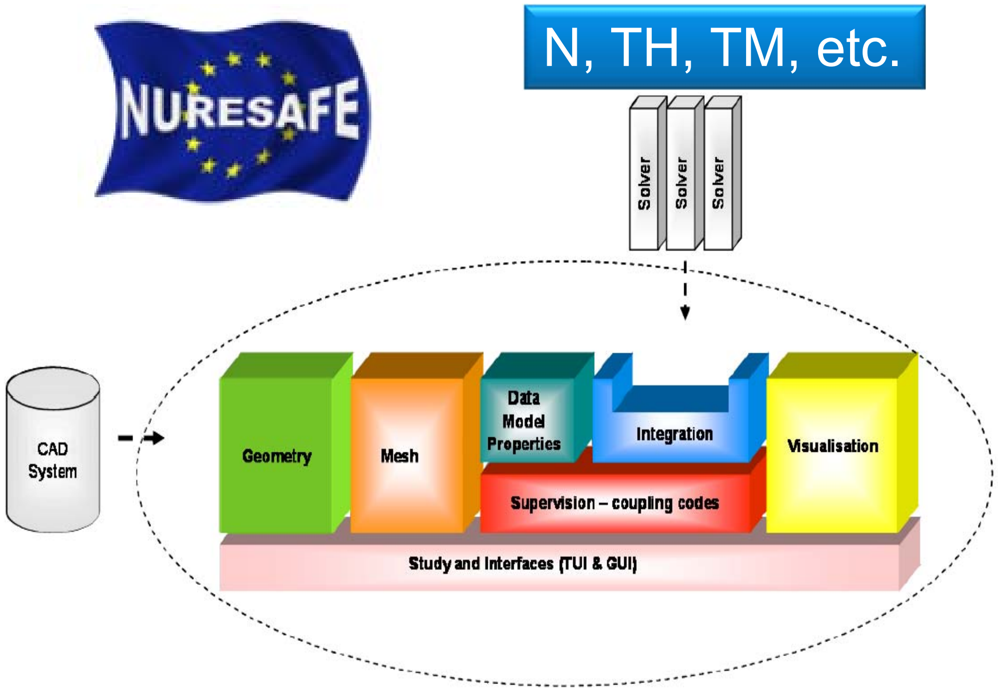
VTT /Finland
- Coupling with SERPENT

Oregon State University / USA
- SMR applications

International

European NURESIM Platform (based on SALOME)

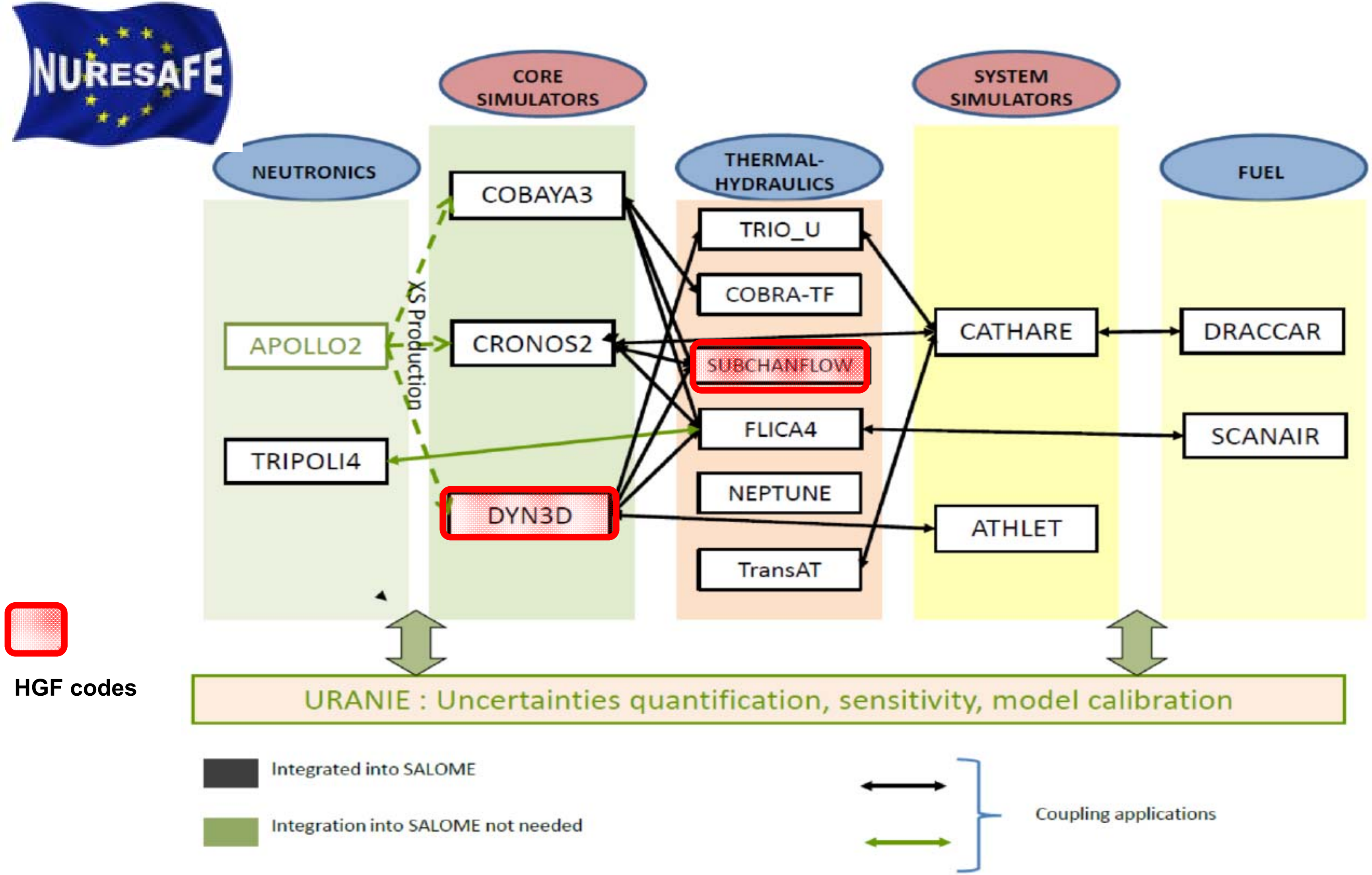
- **The SALOME platform:**
  - Open Source
  - Large user community
- **Peculiarities:**
  - NURESIM components, coupling procedures and input decks
  - Multi-physics coupling based on mesh superposition: N, TH and TM
  - Multi-scale coupling (methods: MEDMED; ICOCO)
  - URANIE for uncertainty &Sensitivity
  - Powerful pre-and postprocessor
  - Parallel capability



SALOME PLATFORM

- **HGF (KIT, HZDR) Contribution to NURESIM (NURISP and NURESAFE Projects):**
  - Integration of DYN3D and SUBCHANFLOW as component
  - Coupling of SUBCHANFLOW with DYN3D, CRONOS and COBAYA3
  - URANIE procedures for U&S quantification of subchannel codes CFT and SUBCHANFLOW

Tools of NURESIM Simulation Platform (NURESAFE)



Coupling of SCF inside SALOME Platform

SUBCHANFLOW

Mesh.med

Field.med

- Feedback exchange
- Data stored in FIELDS.med

DYN3D, COBAYA or CRONOS

Mesh.med

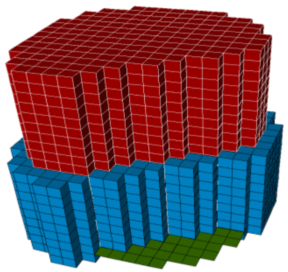
Field.med

Thermal-hydraulic fields
- Fuel temperature
- Coolant temperature and density
- Boron concentration

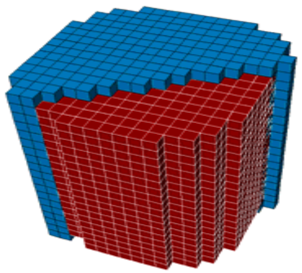
Interpolation

Neutronic fields
- Power density

TH domain

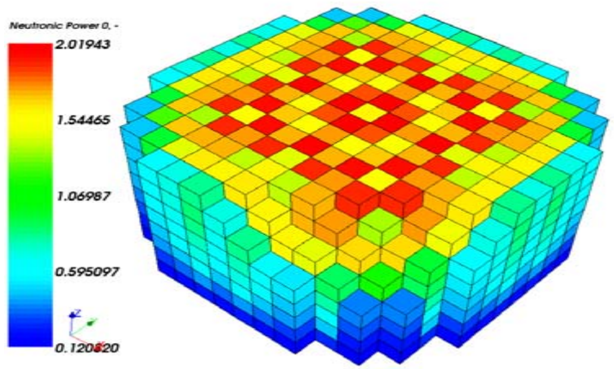


N domain



INTERPOLATION

RESULTS

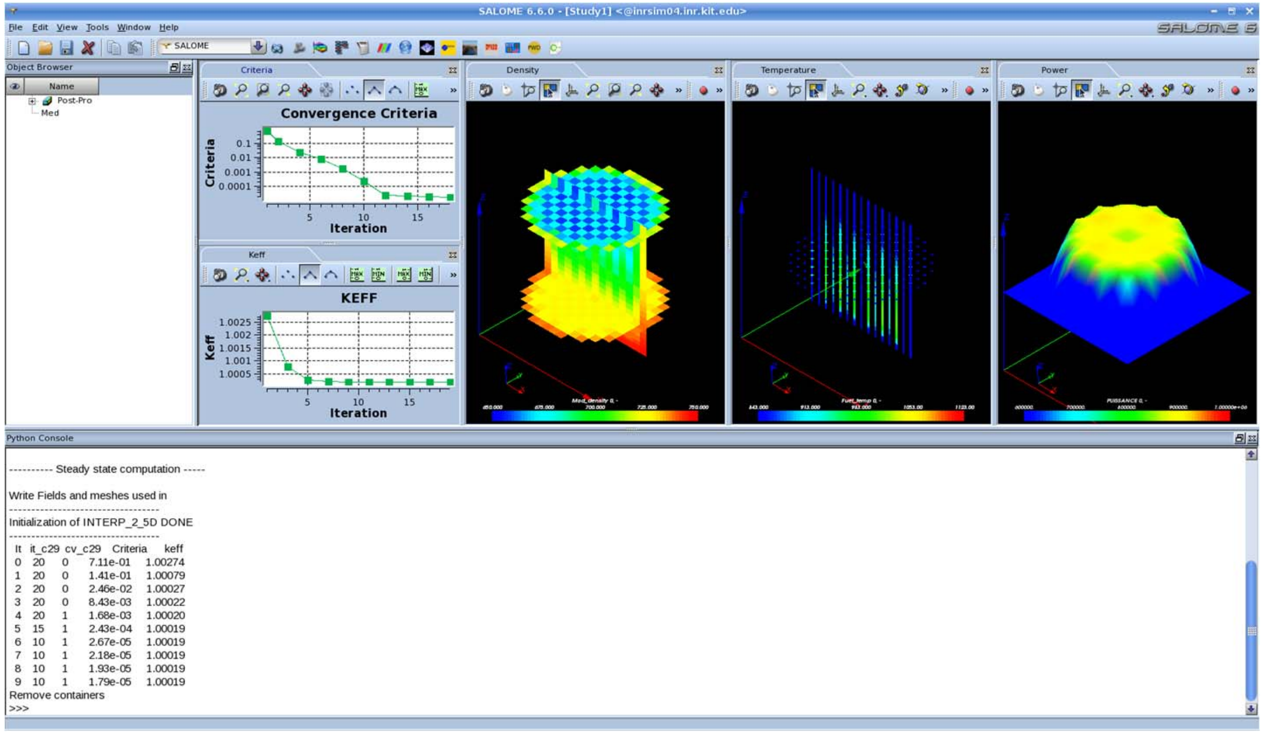


NURESIM Platform: SCF Coupling with RD Codes

Karlsruhe Institute of Technology

- Coupling of SCF with CRONOS - INTERP_2_5D – SCF, python scripts
- Simulation of PWR TMI core HFP conditions

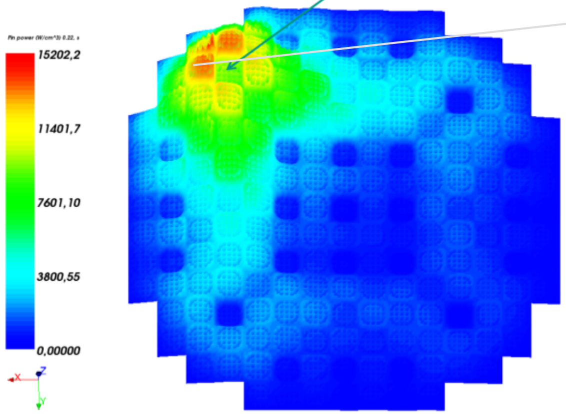
	CRONOS-SCF	CRONOS-FLICA
K_{eff}	1.00019	0.99933



Pin-by-pin
DYNSUB5 Transient Analysis of the PWR MOX REA

DYNSUB5 Analysis of PWR REA

- Simulation: Transient HZP (3.565kW), TC=560 K
- Ejected rod: E5 within 0.1 s
- Time step: 5 ms



Highest power in fresh UOX

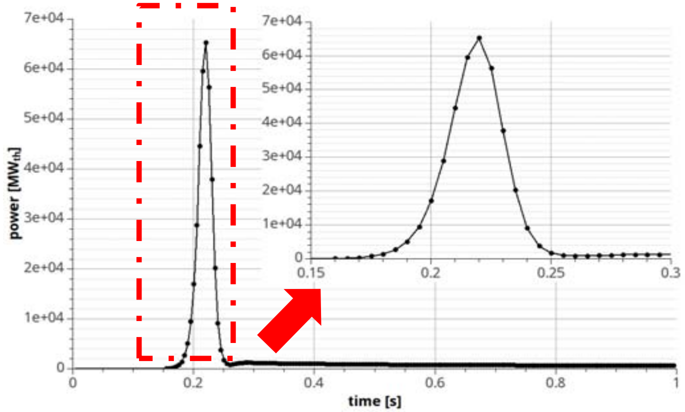
HZP rod ejection accident (REA): axially cumulated power density distribution [W/cm³] at 0.22s

Evident limitations:
- **N-solver: serial code**
- **TH-solver: partly parallelized**

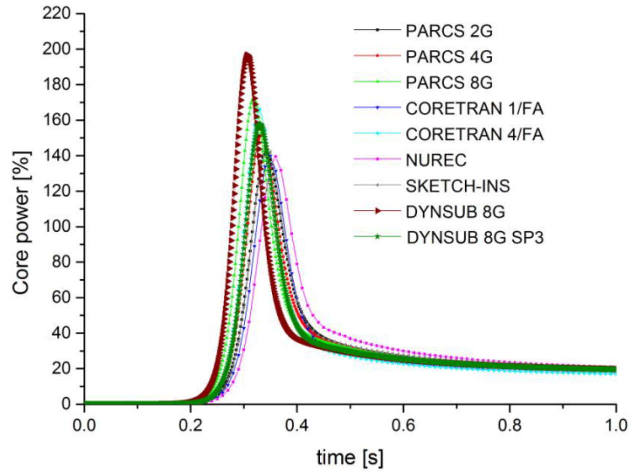
Run statistics:

- Platform: Xeon E5620
- 4 CPUs
- Run time: 14 days and 7 h

Need for validation!



Evolution of thermal power during HZP rod ejection accident (REA)



Code-to-code comparison: Nodal and SP3 Solutions

High Fidelity Coupled code: Serpent2/SCF:

Karlsruhe Institute of Technology

- **Goal: Provide reference solutions for lower order solvers e.g. PPR, SP3**
- **Realization: Internal coupling**

- **Application: PWR MOX/UO2 Benchmark**

U 4.2% 32.5	U 4.5% 17.5	M 4.3% 35.0	U 4.5% 20.0				
U 4.5% (CR-C) 0.15	M 4.0% 0.15	U 4.5% (CR-B) 0.15	M 4.3% 0.15	U 4.2% (CR-SC) 17.5	U 4.5% 32.5		
M 4.3% 17.5	U 4.2% (CR-SB) 32.5	M 4.3% 17.5	U 4.5% (CR-SC) 20.0	U 4.5% 0.15	M 4.3% 0.15	U 4.5% 32.5	
U 4.% (CR-SB) 37.5	U 4.2% 0.15	U 4.2% 22.5	U 4.2% 0.15	U 4.2% (CR-D) 37.5	U 4.5% 0.15	U 4.2% (CR-SA) 17.5	
U 4.5% 0.15	M 4.0% 22.5	U 4.2% 0.15	M 4.0% 37.5	U 4.2% 0.15	U 4.5% (CR-SC) 20.0	M 4.3% 0.15	U 4.5% 20.0
U 4.2% (CR-A) 22.5	U 4.5% 32.5	U 4.2% (CR-C) 22.5	U 4.2% 0.15	U 4.2% 22.5	M 4.3% 17.5	U 4.5% (CR-B) 0.15	M 4.0% 35.0
U 4.2% 0.15	U 4.2% 17.5	U 4.5% 32.5	M 4.0% 22.5	U 4.2% 0.15	U 4.2% (CR-SB) 32.5	M 4.0% 0.15	U 4.5% 17.5
U 4.2% (CR-D) 35.0	U 4.2% 0.15	U 4.2% (CR-A) 22.5	U 4.5% 0.15	UOX 4.5% 37.5	M 4.3% 17.5	U 4.5% (CR-C) 0.15	U 4.2% 32.5

Core data: 193 Fuel assemblies

Quantity	Value
Power	3565 MW
Core mass flow rate	15849.4 kg/s
Inlet pressure	15.5 MPa
Coolant inlet temperature	560 K

SERPENT/SCF pin-by-pin model:

Core model at subchannel level:

- Neutronics nodes: 55777 pins and guide tubes
- Thermal hydraulics: 35 axial levels, 62532 sub channels
  - **Fluid: 2.2 M cells, Solid: 23.4 M**

MC parameters per iteration step:

- 4 E6 neutrons per cycle
- 650/2500 inactive/active cycles

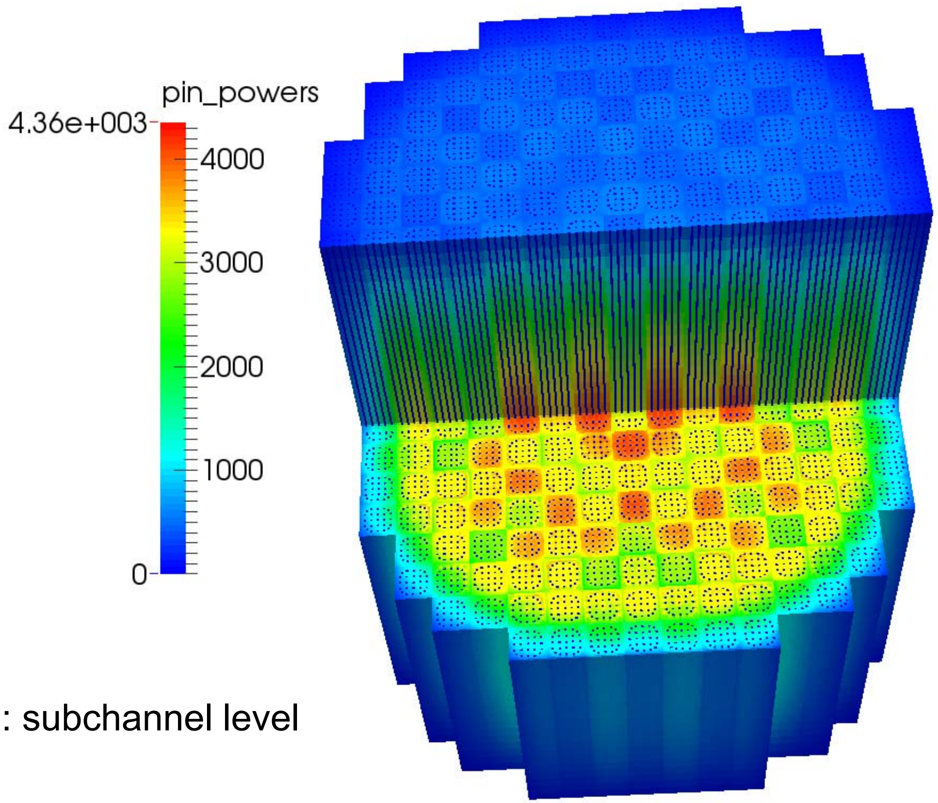
Convergence criteria:

- T-Doppler and M-density= < 0.5 %

Serpent2/SCF:
High fidelity Simulation of the HFP PWR MOX/UOX Core (2/2)

Karlsruhe Institute of Technology

5M neutrons per cycle, 2000 active cycles per iteration



TH: subchannel level

SSS2/SCF: 3D Power Distribution

Prediction of hottest pin considering local feedbacks possible!

- **SSS2/SCF Simulation at KIT IC2 HPC Cluster: Intel Xeon E5-2670, InfiniBand**

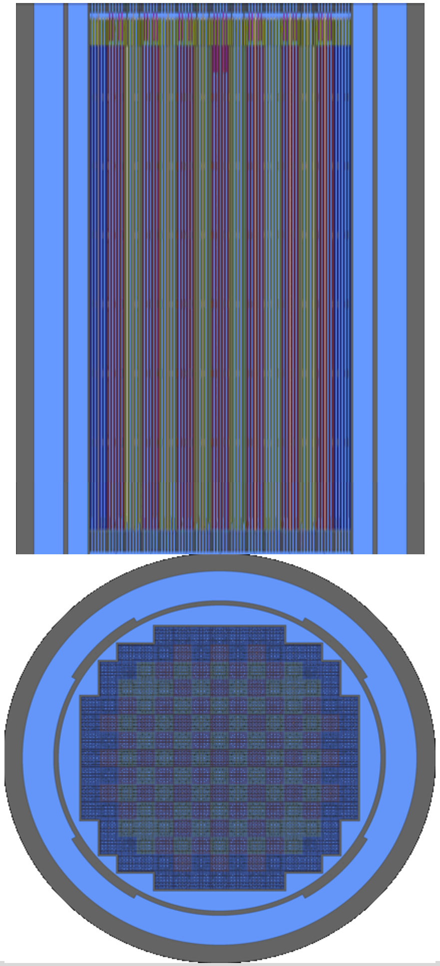
- **KIT IC2 HPC: 16 to 2048 cores (1 to 128 nodes)**
- **5.8 CPU-Y= 5.8 x 365 d / 2048 = 1.03 days**

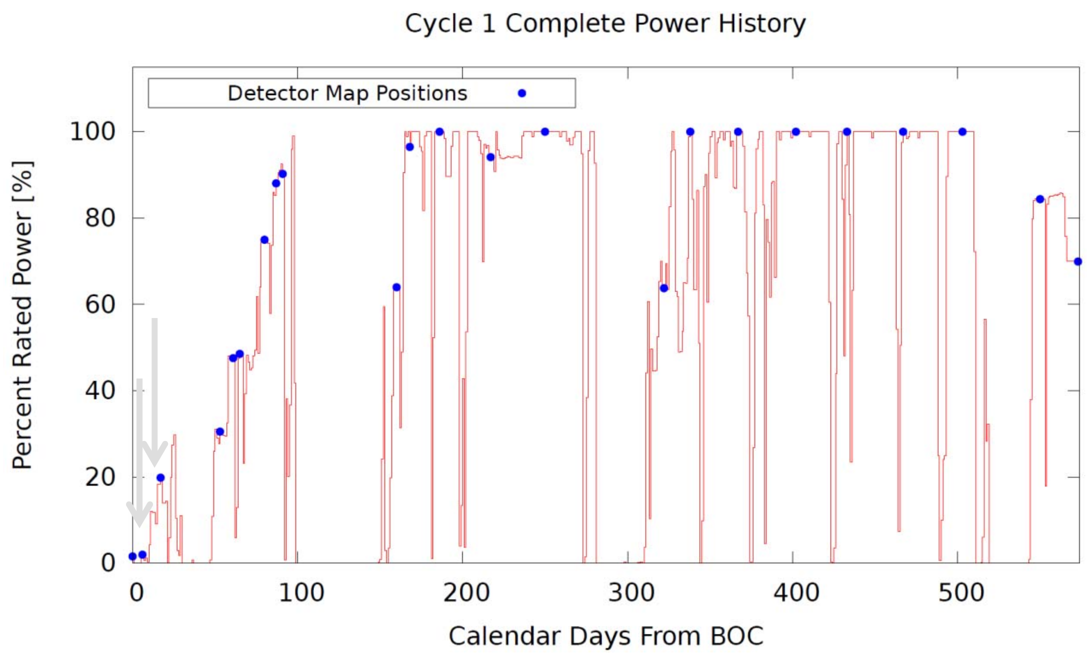
KIT IC2: one node of 16 cores: 64 GB memory

Validation of SERPENT2/SCF:
PWR Cycle 1 (MIT BEAVRS Benchmark)

HZP physics tests (25 MWth)

HP measurements at 18 calendar days (692.7 MWth) after BOL





BEAVRS Cycle 1: power history

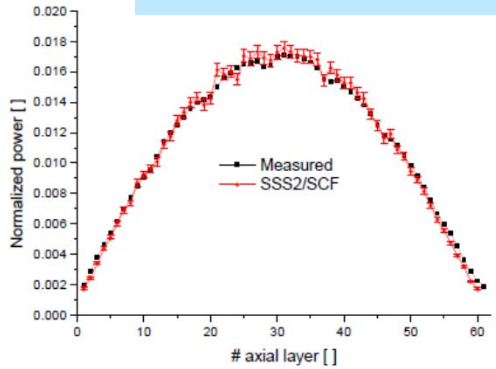
SERPENT2/SCF Validation

MIT BEAVRS benchmark

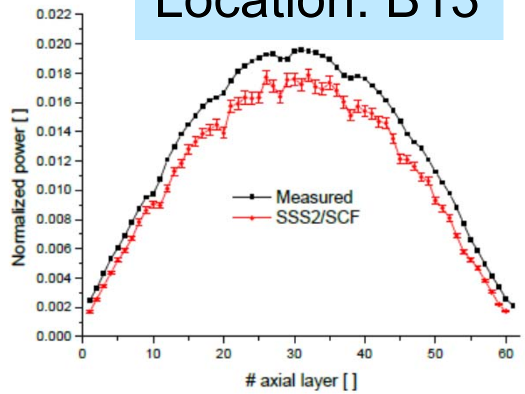
- HZP physics test
- HP measurements at 18 days (693 MWth) after BOL

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							0.62			0.09					
2			5.70			7.06		2.55							
3								3.58		1.12		1.63		-0.18	
4		5.97	5.64					5.00							
5					8.62				4.39		2.49		3.80		
6	3.51		4.67			6.02		5.08						2.27	
7				3.78			4.13			2.81			0.32		
8	1.60		3.85		2.36		1.86			0.83		-0.47	-2.62	-2.01	
9		1.42							2.91		0.36				-6.98
10					1.29		-0.65					-5.25			
11	-1.38				0.25			-3.30			-3.48				-9.48
12						-0.36			-6.17			-7.53			
13			-3.45		1.68			-5.54						-13.24	
14			-2.74				-7.61			-7.16		-10.37			
15					-5.62			-9.99							

Location: B03



Location: B13

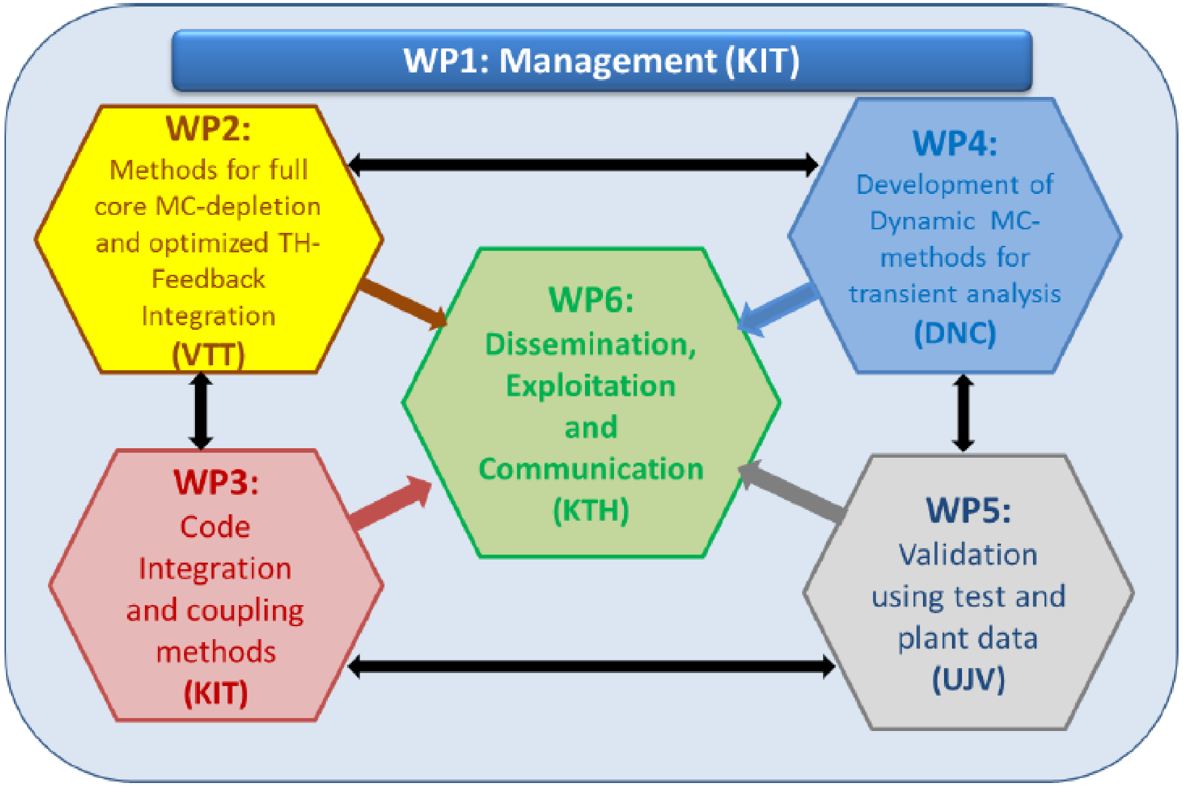


M. Daeubler, L. Mercatali, V. Sanchez, R. Stieglitz und R. Macian-Juan, „Validation of the Serpent 2-DYNSUB code sequence using the Special Power Excursion Reactor Test III (SPERT III),“ p. Submittet to ANE for publication, 2015.

H2020 McSAFE Project: (Start: 1.9.2017 end: 31.8.2020)
High Performance Monte Carlo Methods for SAFEty Demonstration

Karlsruhe Institute of Technology

Karlsruher Institut für Technologie



Delft Nuclear Consultancy

EUROPEAN COMMISSION

www.mcsafe-h2020.eu

CEZ GROUP

KTH ROYAL INSTITUTE OF TECHNOLOGY

KIT Numerical Simulations for Severe Accidents(2/2)

- **Severe accidents research for LWR**
  - Code development
    - GASFLOW
    - Code coupling e.g. MELCOR/GASFLOW
  - Code validation and application
    - **ATHLET-CD**
    - MELCOR
    - **ASTEC**

Latest applications: Optimization of SAMG for German PWR and BWR

LWR

- **Severe accident codes for GEN-IV**
  - Code development for initiation phase:
    - SAS-SFR
    - PARCS/SAS-SFR
  - Code development and validation for transition phase and late phase:
    - **SIMMER multi-physics code**
    - ASTEC-Na (under development)

Latest applications: SFR, LFR, ADS, MSFR

GEN-IV

LWR Severe Accident Investigations for the Optimization of SAMG

KIT Activities for Accident Management

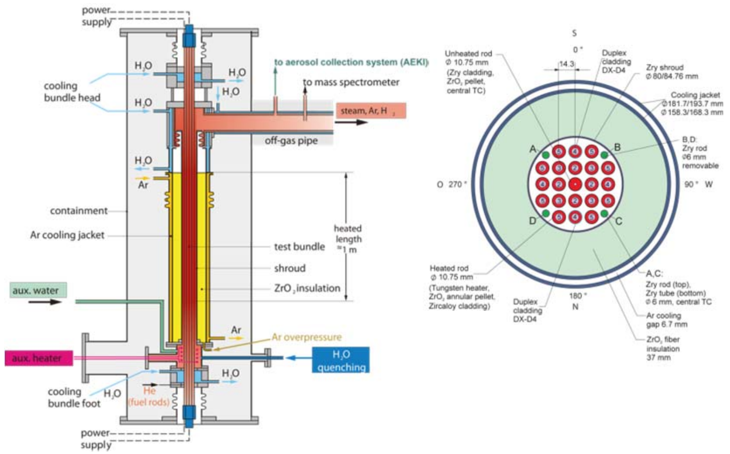
- Goal:
  - Evaluate the capability of simulation tools for SA-sequences
  - Extend the technical basis for SAM-optimization
- KIT activities:
  - German WASA-BOSS project of universities and research centres (PWR, BWR)
    - ATHET-CD code
  - Participation in different EU projects e.g. EU CESAM, FASTNET, IVMR (22 partners, PWR, VVER, BWR, PHWR)
    - ASTEC code
- Use of KIT experimental facilities such as QUENCH, LIVE, etc. to validate SA codes

KIT Activities for Accident Management

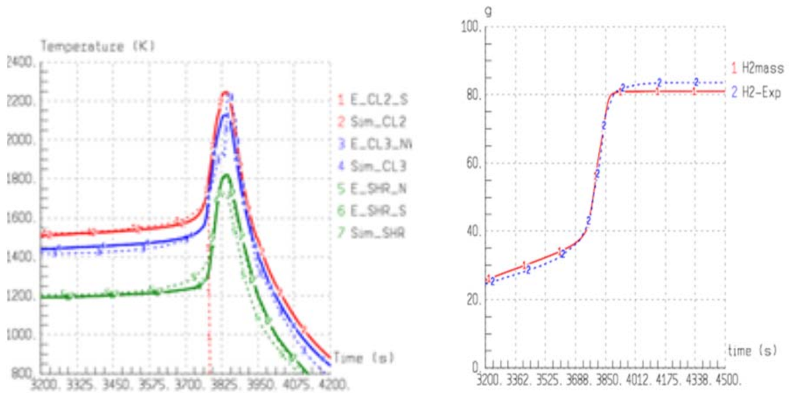
Karlsruhe Institute of Technology

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

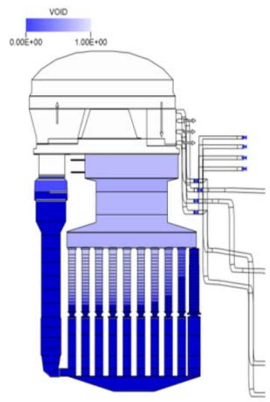
- **Optimization of accident management for German PWR and BWR**



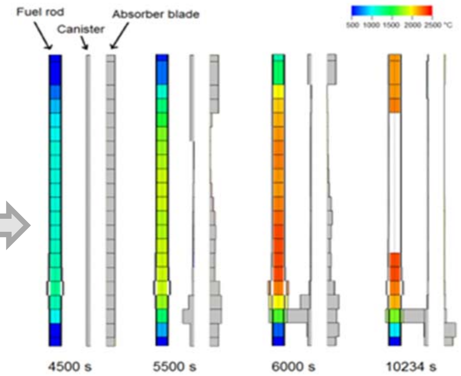
QUENCH Test Facility: Severe accident phenomena



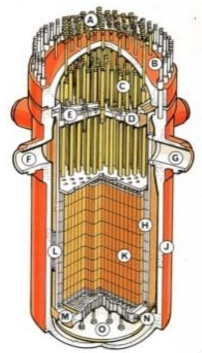
Simulation vs. Data: Temperature and hydrogen



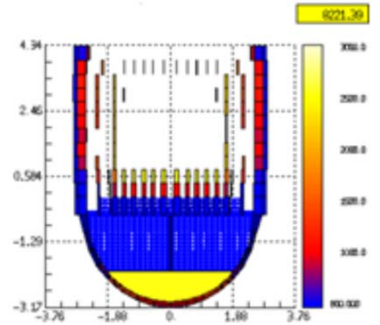
BWR Plant



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



PWR RPV



ASTEC: RPV state before Failure

Summary

Karlsruhe Institute of Technology

- **Investigations are focused on**
  - experiments
  - Modelling and simulations
- **Experimental investigations covers both LWR and innovative reactors**
  - Design basis accidents and
  - Severe accidents
- **Key activities are:**
  - Provide key-data for code validation
  - Develop own codes complementary to external codes
  - Perform code validation and application
- **Activities are embedded in national and international co-operations**
- **Strategic partnerships with key-players is very important**