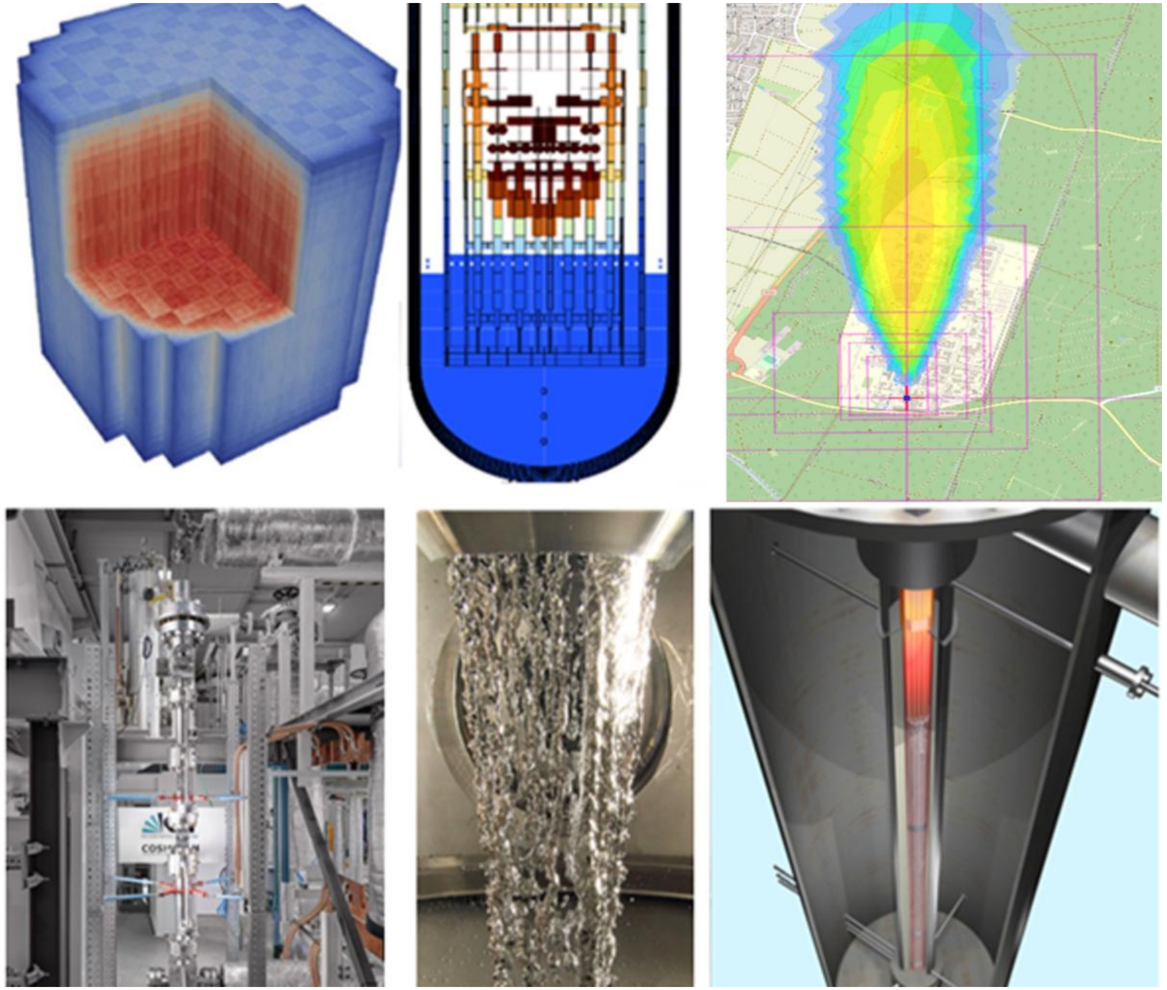
The KIT Computational and Experimental Framework on Severe Accident Research



Fabrizio Gabrielli

Karlsruhe Institute of Technology (KIT)

Institute for Neutron Physics and Reactor Technology (INR)

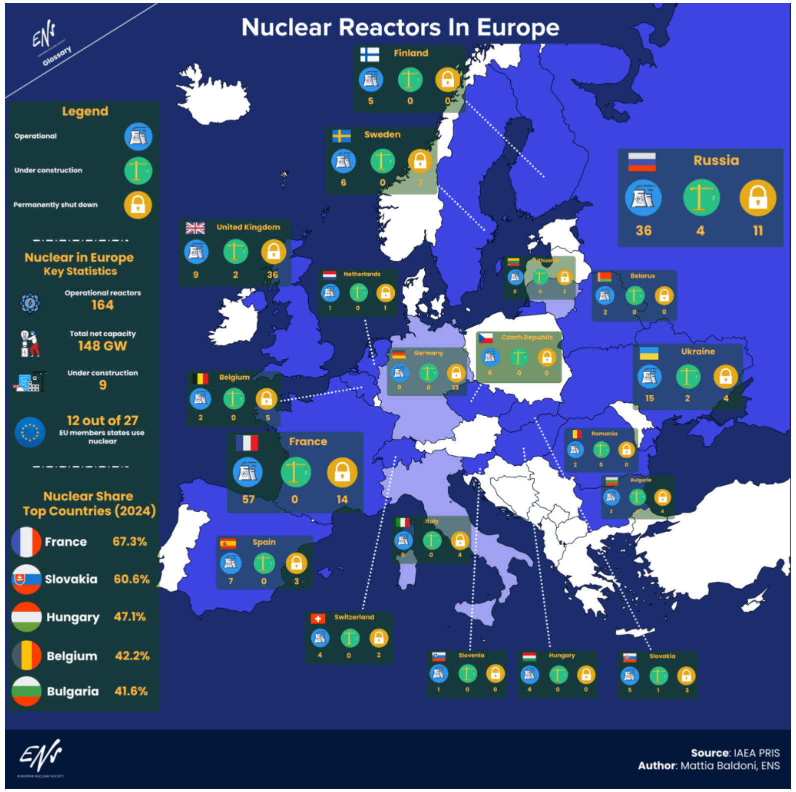
Reactor Physics and Dynamic Group (RPD)

Motivation

- Framework: Helmholtz NUSAFE long-term Research Program

- Many and different NPPs under operation and going to be deployed around Germany and worldwide

- Mission:
  - **Keeping and improving expertise and knowledge** to support the **assessment of the hypothetical risks** that may arise from the operation of current operating and innovative designs NPPs, e.g., LWRs, SMRs, AMRs, Gen.IV



https://www.euronuclear.org/glossary/nuclear-power-plants-in-europe/

Strengthen the **Helmholtz Simulation Platform** by combining large-scale test facilities and advanced simulations for the **safety assessment,** the **Environmental Impact Assessment (EIA),** and the **Emergency and Preparedeness Response (EP&R)** highly relevant to operating and advanced NPPs in the EU and worldwide

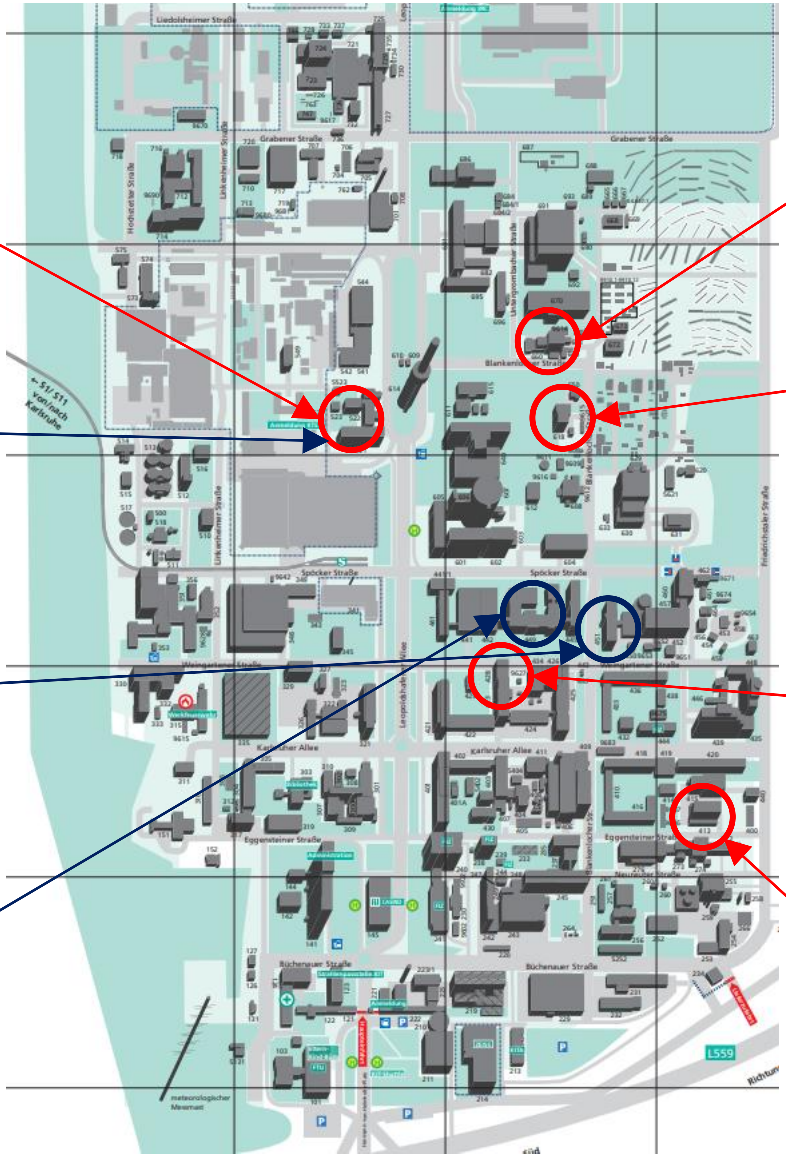
The Current KIT (Campus North) Wonderland

KASOLA
TH Sodium

Simulation groups
Reactor Safety

Simulation group
JRODOS

High-performance computing centre



HELOKA-US
TH MSR

QUENCH
TH+Materials

COSMOS-L and -H
TH+Materials

KALLA
TH+Materials
(Pb and Pb/Bi)

Water-cooled Nuclear Reactors' Safety

Large-Scale Facilities and Calculation Platform

ATF cladding research at KIT

- HT behavior of all promising cladding materials
  - Cr-coated Zry, FeCrAl, SiC-based composites
- Separate-effects tests and bundle experiments
- Model development, code validation and code application
- Embedded in international cooperation programs
- and further international collaboration, e.g., with CEA, ASNR (France), Westinghouse (USA) and SNU (South Korea)

Source: https://de.wikipedia.org/wiki/Datei:Eugene_F._Kranz_at_his_console_at_the_NASA_Mission_Control_Center.jpg

- See, M. Steinbrück, *QUENCH-ATF: Status and Outlook*, Technical session 4

(courtesy of J. Stuckert, M. Steinbrück)

The COSMOS and QUENCH Large-Scale Facilities
ATF-related activities

QUENCH+COSMOS: covering the entire range from normal operation to DBA and BDBA

COSMOS Facility

- Experiments on two-phase flow with heat transfer
- **Flow boiling phenomena including critical heat flux for classical and ATF materials**

QUENCH Facility

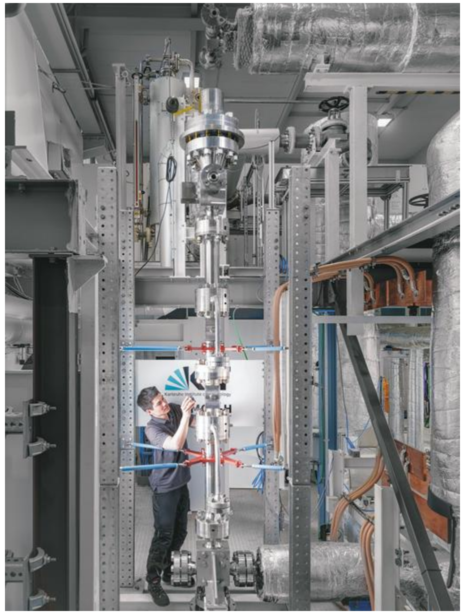
- Investigation of hydrogen source term during early in-vessel phase and effect of reflood
- **Current focus on ATF cladding materials**

(courtesy of S. Gabriel)

COSMOS Large Scale Facilities

COSMOS-L Low Pressure Water loop

- Water loop @0,3 MPa and 160°C
- Thermal power 150 kW – 300 kW, including 70 kW for the test-section
- More the 1000 CHF-events on different heater geometries (single tube, bundle of 5 tubes, flat heater for IVR-ERVC experiments)
- Pre-experiments for COSMOS-H



COSMOS-H High Pressure Water/Steam Cycle

- **New TH facility (commissioned in 2025)**
- Water/Steam loop @17 Mpa and 370°C
- Thermal power 1.8 MW including 600 kW for the test section
- Test section: single tubes and small bundles (3x3) up to 3.5 m length
- 1:1 conditions to most of the LWR Concepts
- **Flow boiling phenomena** including **CHF**
- **Optical measurement** technology under **high pressure conditions**

Experiments in BWR, PWR, and SMR conditions.

COSMOS-H and COSMOS-L

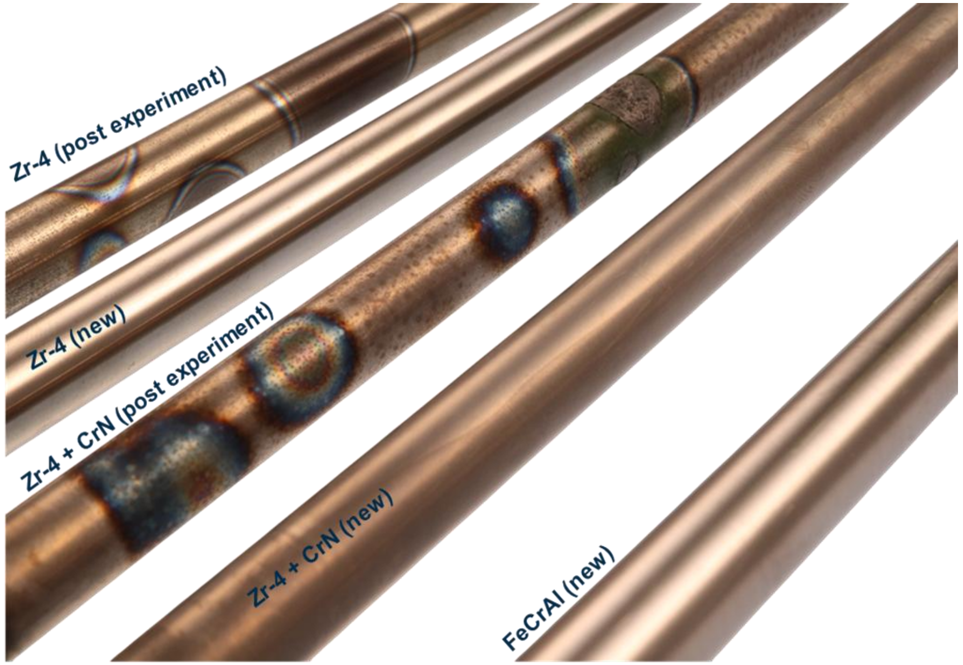
(Courtesy of S. Gabriel)

ATF-related activities at COSMOS Lab

- Investigating heat transfer in ATF-Claddings from normal operation to CHF

- COSMOS-L allows comparing the heat transfer among:
  - different cladding materials (Zr-4, Cr-coated Zr-4, FeCrAl)
  - manufacturing processes (Coldspray, PVD, chemical coating)

- EU OFFERR-Chrotemp project: investigating various ATF materials in post-DNB conditions

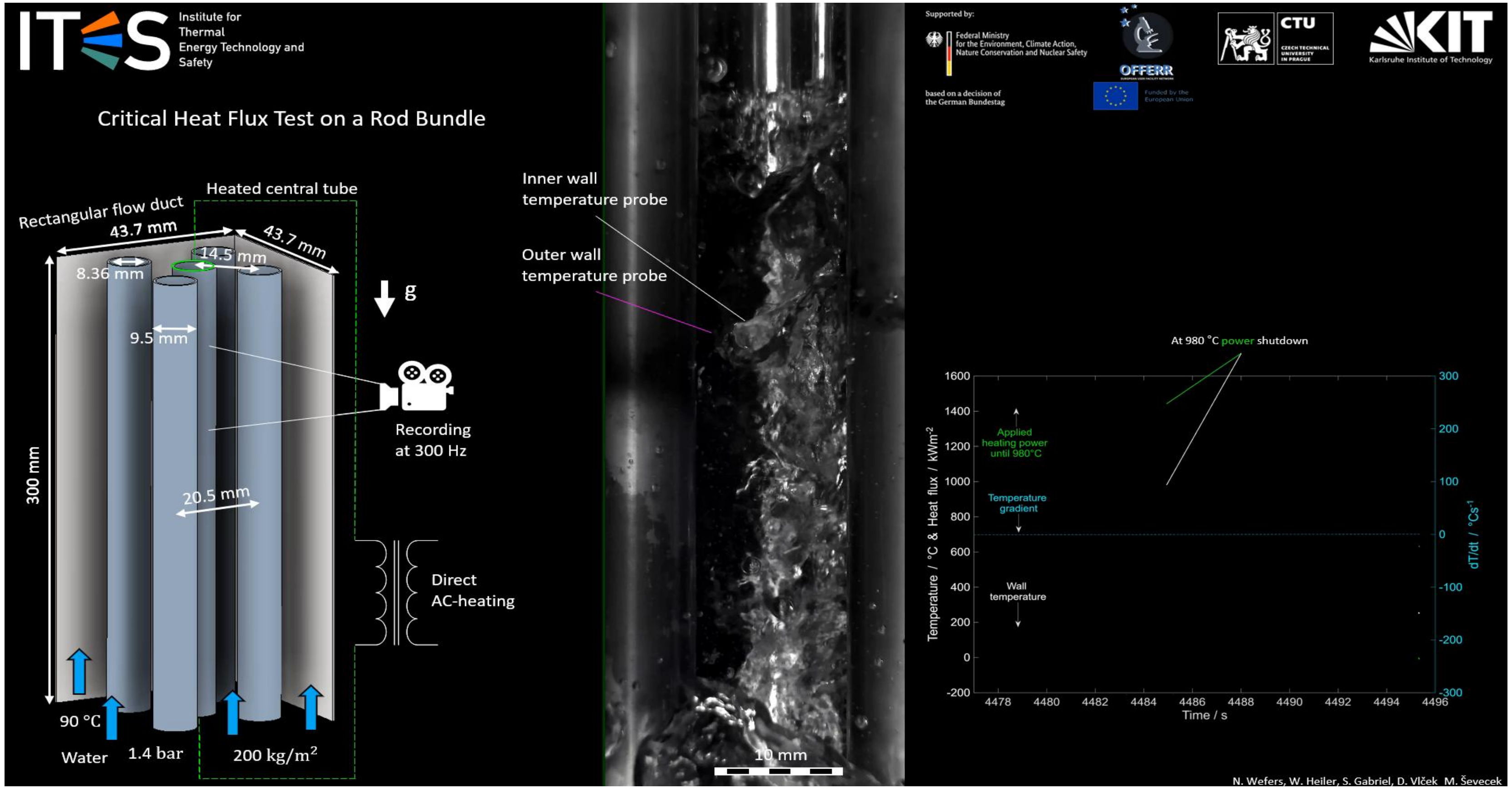


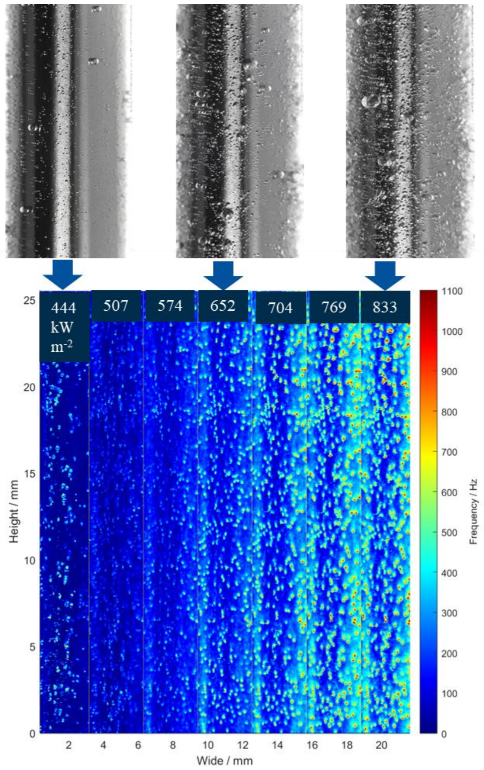
OFFERR
EUROPEAN USER FACILITY NETWORK

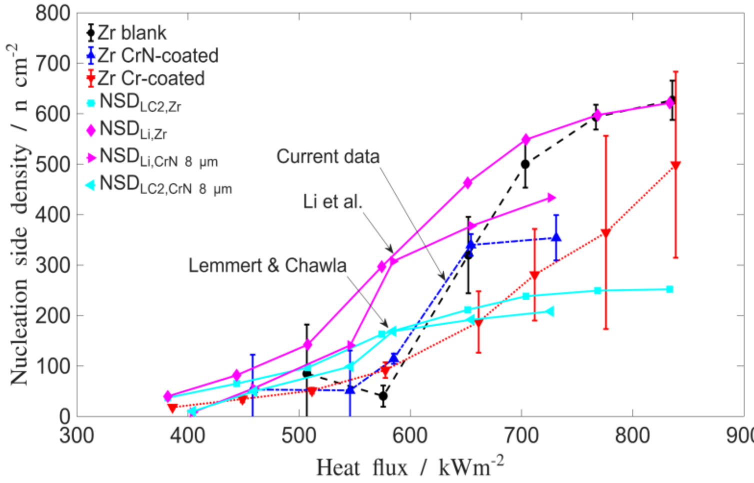
Funded by the European Union

COSMOS-H and COSMOS-L
ATF-related activities at COSMOS Lab

- Investigating the heat transfer of Cr-coated Zr and FeCrAl ATF materials under normal and DBA conditions



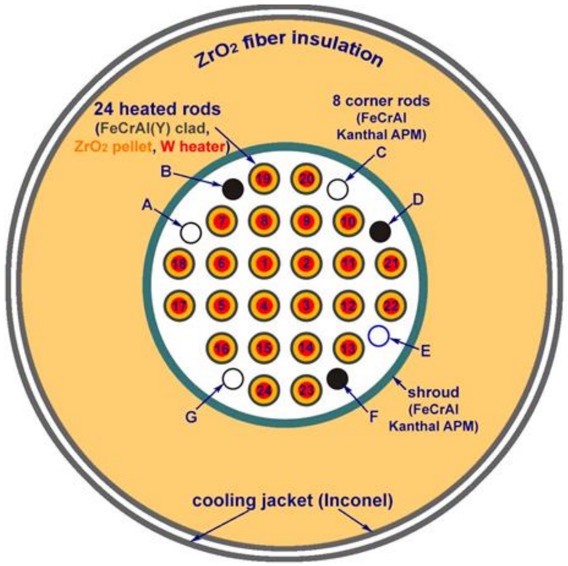


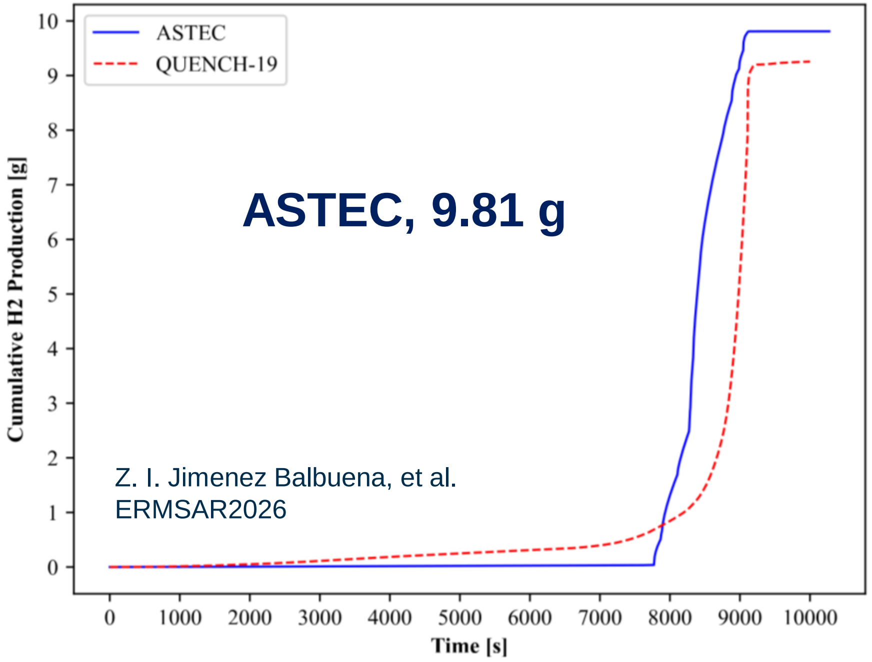


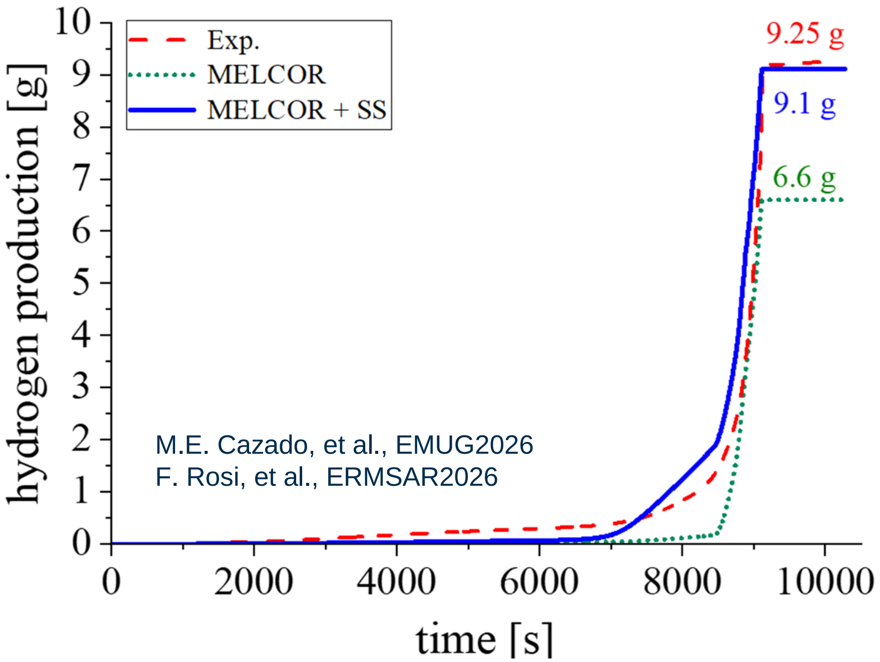
(courtesy of S. Gabriel)

Validation of Severe Accident Codes
ASTEC and MELCOR validation against QUENCH-19

- **QUENCH Experimental data employed**
  - **Separate-effects tests** for the development of physical models
    - Provision of correlations for cladding oxidation
  - **Bundle-tests** for the **validation of integral codes** in representative conditions







- See, M. E. Cazado, *MELCOR Validation Against the QUENCH-19 Experiment and Outlook on ATF-Related Activities*, MELCOR Code Assessment Program -Session 2

KIT Strategy for Severe Accident Analyses
Mission and Strategy

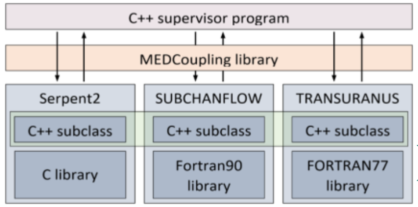
Realistic estimation of the source term and **dispersion of fission products** (radiological risk) into the environment

Use of **state-of-the-art codes** at each simulation stage.

Going beyond: Development, extension, and validation of integral codes by using the KIT experiments.

- **Fuel inventory and decay heat**
  - Neutronic codes (CASMO, SCALE, Serpent)
- **Severe accident progression**
  - Integral codes (ASTEC, MELCOR, SIMMER, CONTAIN-LMR….)
- **Uncertainty quantification of the source term**
  - KATUSA tool (KIT development)
- **EIA and EP&R**
  - JRODOS (KIT development)
- **Improving the codes‘ performance**
  - AI/ML algorithms
- **Strategic international cooperations** (US NRC, ASNR, JAEA/CEA, NRA, CNL, ….)

Calculation Platform for SA Analyses

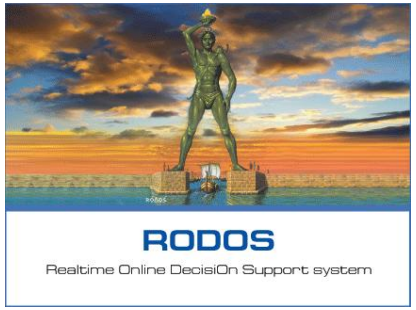


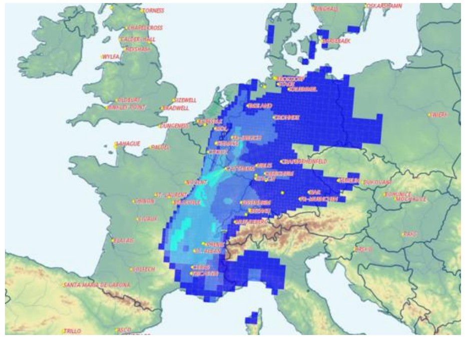
CASMO

ASTEC
ACCIDENT SOURCE TERM EVALUATION CODE

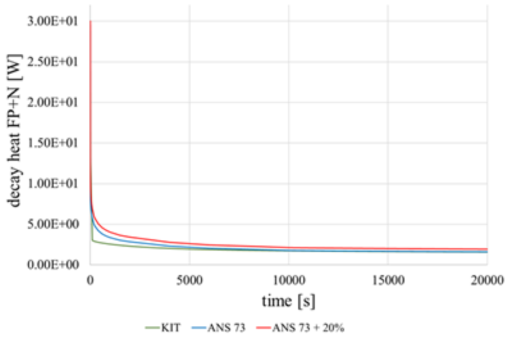
MELCOR

KATUSA

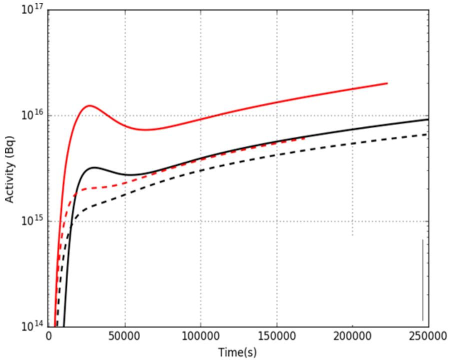




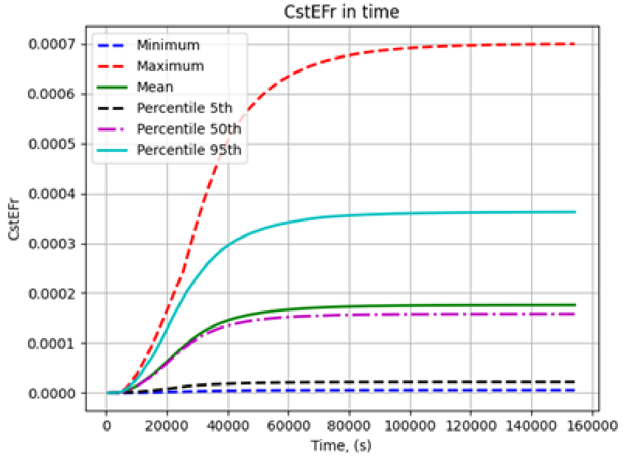
- **Fuel inventory**
- **Decay heat**



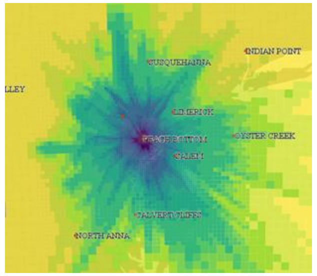
- **Accident progression**
- **Source term**



- **Uncertainty and sensitivity analyses of the source term**



Statistical Analysis and/or AI/ML



Risk Map

- **Environmental Impact Assessment**
- **Emergency Response and Preparedeness**

(courtesy of O. Murat)

O. Murat, et al., 2025, https://doi.org/10.1016/j.anucene.2025.111277
O. Murat, et al., 2023, https://doi.org/10.1016/j.nucengdes.2023.112227
A. Mercan, et al., 2022, https://doi.org/10.1016/j.nucengdes.2022.112078

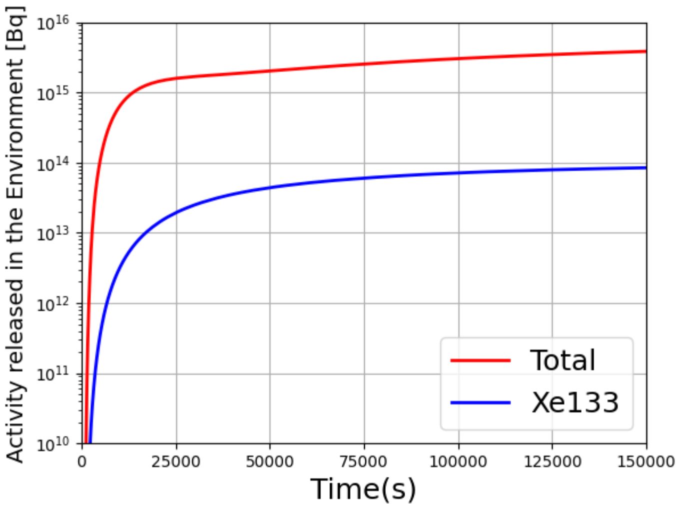
Reactor Physics and Dynamic
INR KIT

KIT Computational Chain for Radiological Impact Prediction
ASTEC and JRODOS coupling

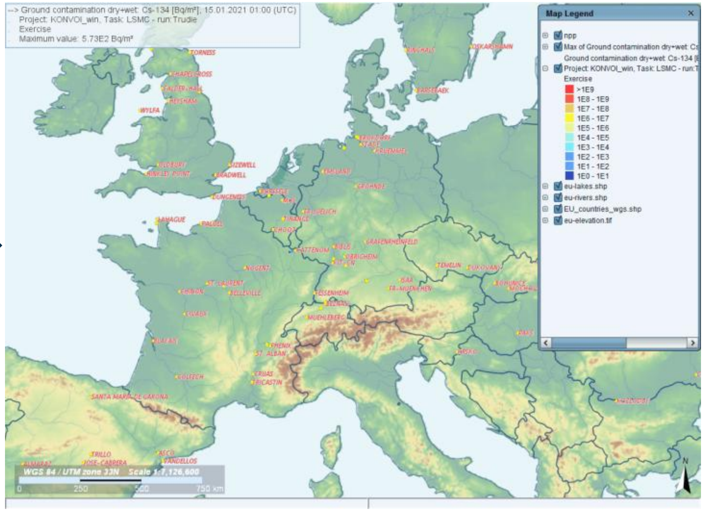
Once-through approach from fuel inventory to the dispersion of the fission products in the environment **by using state-of-the-art codes.**

ASTEC
ACCIDENT SOURCE TERM EVALUATION CODE

Source Term
Isotope-wise activity release



Cloud arrival time [hours]



O. Murat, et al., 2023, https://doi.org/10.1016/j.nucengdes.2023.112227
A. Mercan, et al., 2022, https://doi.org/10.1016/j.nucengdes.2022.112078

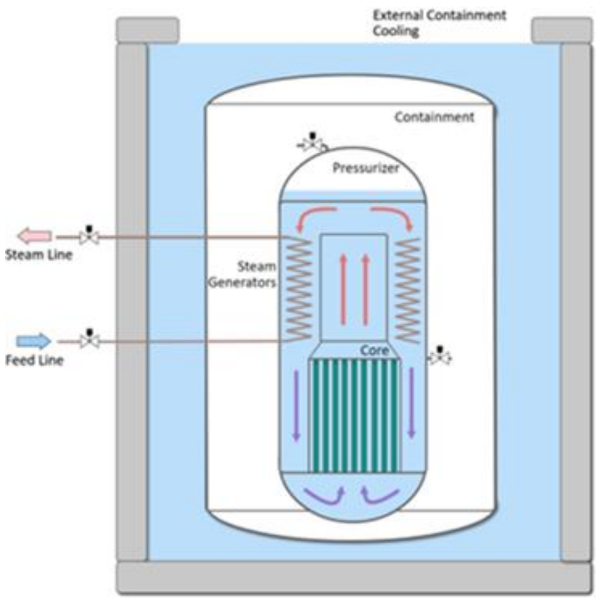
Reactor Physics and Dynamic

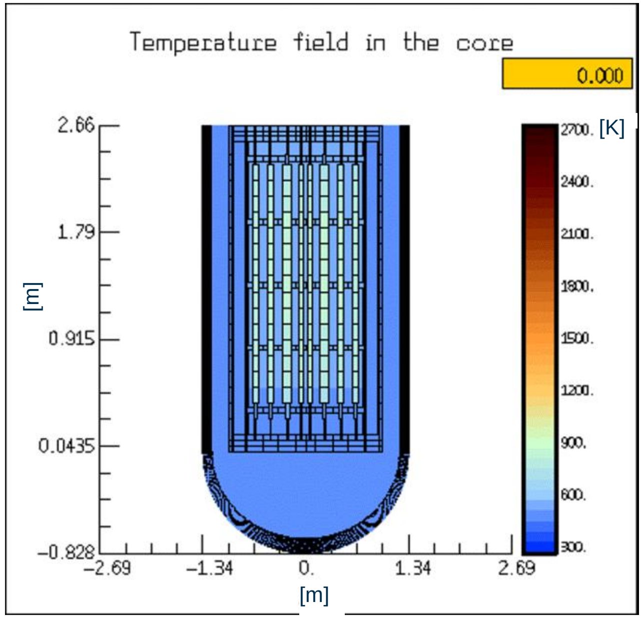
Severe Accidents Analysis & AI Methods for Reactor Safety

Highlight: SMR Analysis

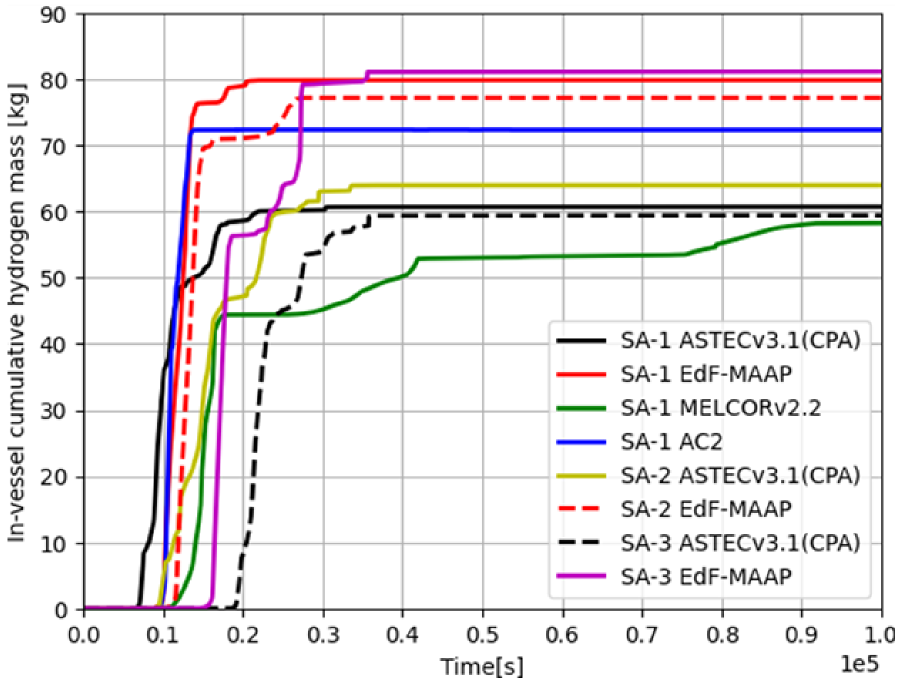
- KIT as Working Package leader

(courtesy of M. E. Cazado)





Design-1



Outlook: Estimation of the radiological risk after postulated severe accidents in a water cooled SMR

F. Gabrielli, M.E.Cazado, et al., 2026, ERMSAR

Severe Accidents Analysis & AI Methods for Reactor Safety

Highlight: EU ASSAS project

- Building a SA simulator for a Western-type PWR based on the ASTEC code
- KIT as Working Package leader
- ASSAS DataHub at KIT : Large Scale Data Facility (LSDF)
  - Developed by the KIT Scientific Computing Center (SCC)
  - Based on FAIR principles – Findable, Accessible, Interoperable, Reusable

Source: https://www.scc.kit.edu/en/research/11843.php

17
Registered users
Researches with platform access

1102
Available Datasets
ASTEC simulation datasets

76.56 TB
Binary storage size
Binary simulation data

2.3 TB
HDF5 storage size
Hierarchical data format

204
ASTEC variables per dataset
Typical number of variables per dataset

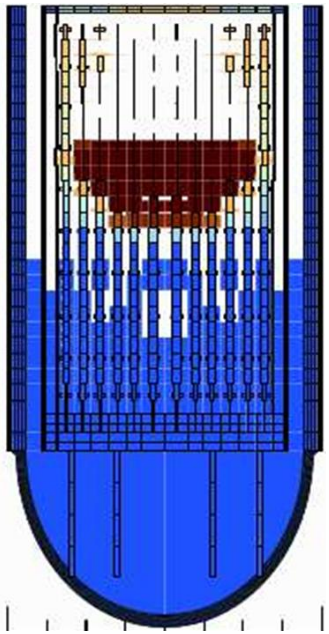
A. Stakhanova, et al., 2026, ERMSAR

Reactor Physics and Dynamic

Severe Accidents Analysis & AI Methods for Reactor Safety
Surrogate Model of the Vessel

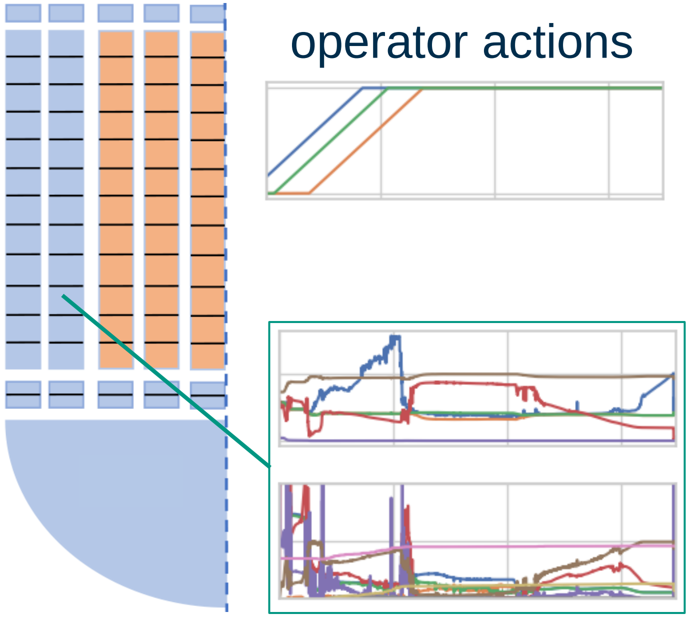
HELMHOLTZ AI Artificial Intelligence Cooperation Unit

Physical domain



Westinghouse pressure vessel
internal volume
assumption: no external influence

data from ASTEC model



76 mesh elements
15 field variables
15 operator actions

76 x 15
= 1140 DoF
per time step

modeling task

X(t+1) = f(**X**(t), c(t), c(t+1))
(autoregression)

X: state variables
c: operator actions
f: neural network

requirements

- fast rollout
- high accuracy
- model extensibility

(courtesy of P. Kieckhefen)

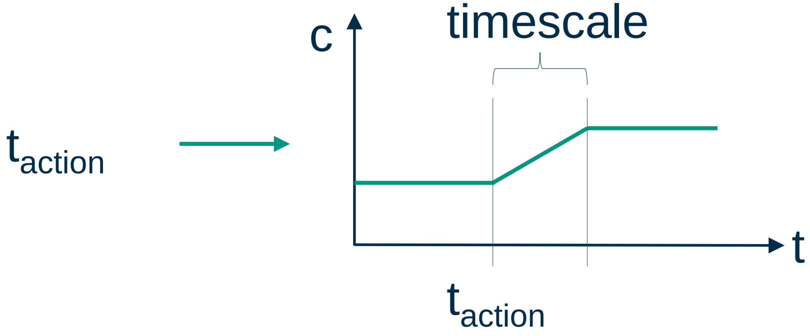
Reactor Physics and Dynamic

Severe Accidents Analysis & AI Methods for Reactor Safety
Surrogate Model of the Vessel

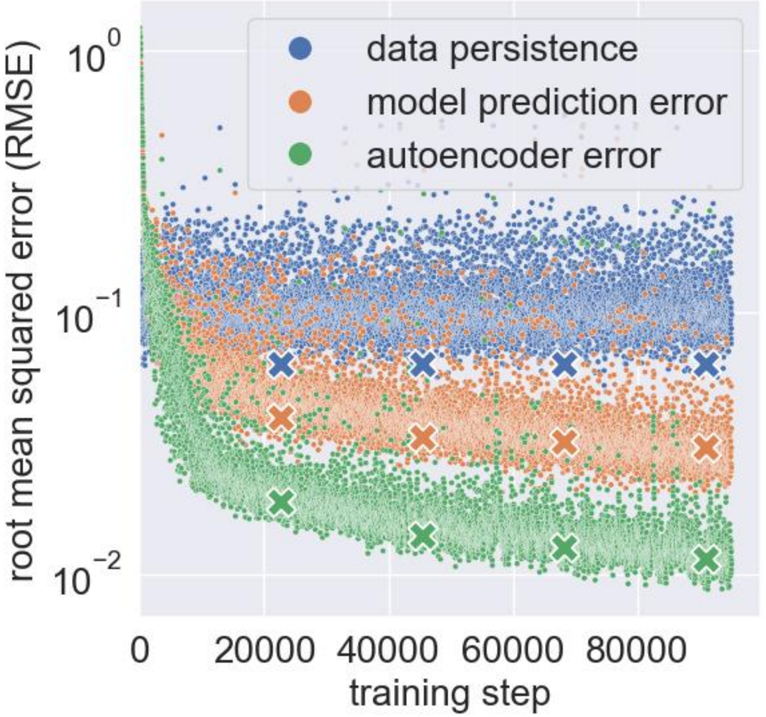
HELMHOLTZ AI Artificial Intelligence Cooperation Unit

Data Preparation

1. Extract **/vessel/mesh** values from HDF5, normalize & smoothen (scale: 60 s)
2. Extract **operator actions** and turn into time series with time scale information
3. Write into compressed HDF5



Model training



130 million parameters
30 s time step
3 h / epoch (880 scenarios) on 4xA100

(courtesy of P. Kieckhefen)

16 ms per inference step (A100), 7 h simulation in 15 s wall time

Reactor Physics and Dynamic

JRODOS: Java Real-time On-line Decision Support System
KIT developed tool for radiological impact prediction

(courtesy of W. Raskob, S. S. Ottenburger)

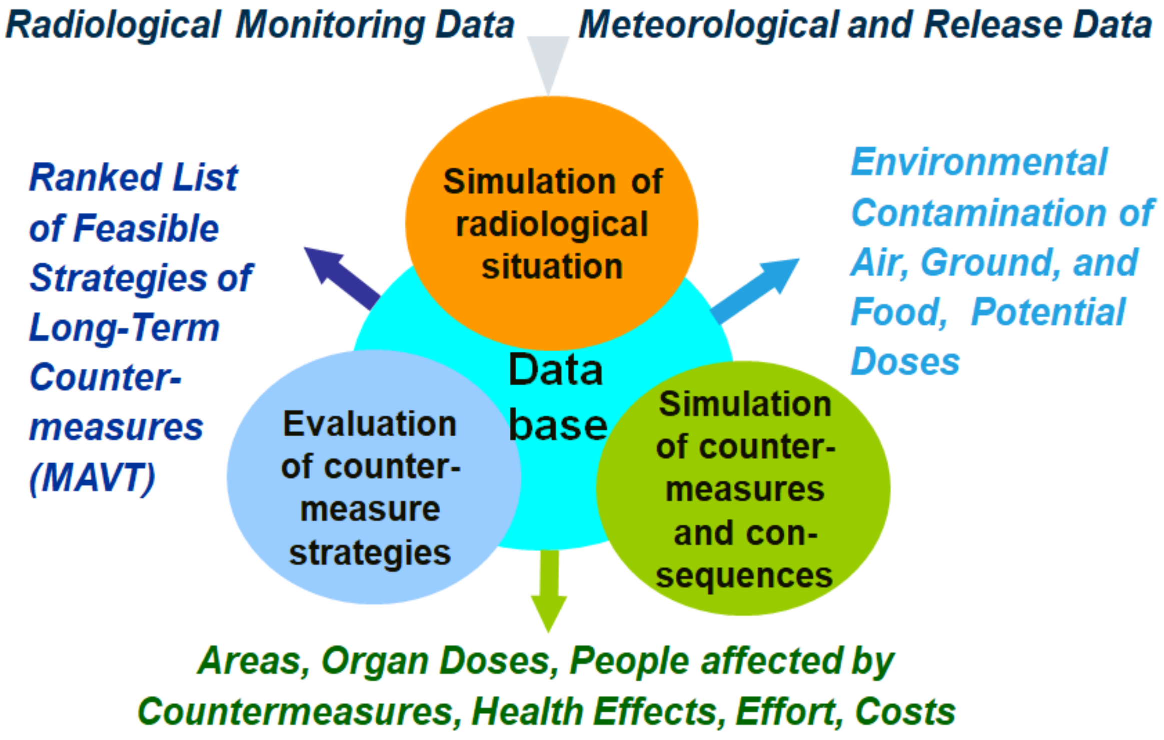
- Simulation of **radionuclide release and environmental impact on fall out zone in early and later phase of an accident**

Enhancing emergency planning capabilities for decision-maker on **local/national/international scales** for all **relevant emergency actions and countermeasures**

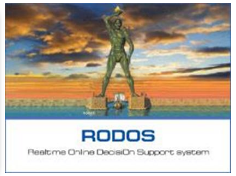
One or several users in about 50 countries worldwide (governmental authorities, local communities, research centers, universities, NPP operators, etc.).

W. Raskob, 2012, https://doi.org/10.1051/radiopro/20116865s

RODOS simulation procedure

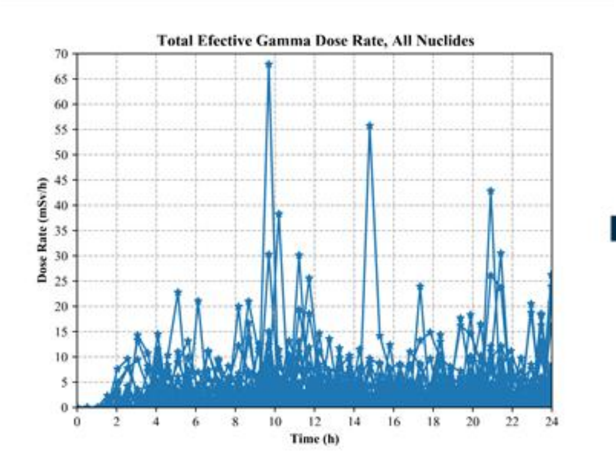


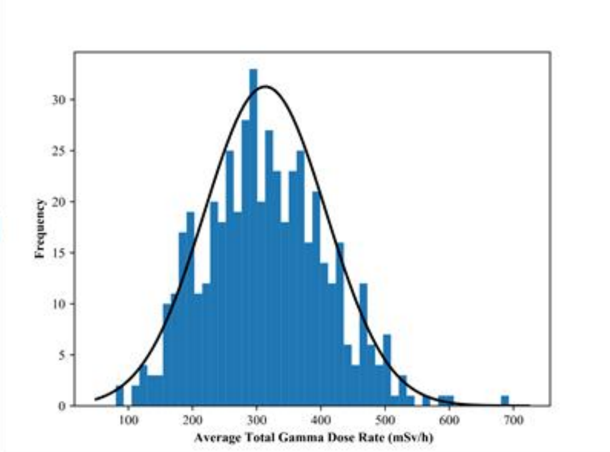
Presently simulating every hour scenarios for four NPPs in Ukraine.



Rapid Prediction of Atmospheric Radioisotope Dispersion
Artificial Neural Network (ANN) Surrogate Approach

- Comprehensive risk assessments covering multiple calendar years and thousands of weather scenarios are computationally prohibitive





JRODOS Simulation of large batches requires **years of CPU time**

60,000 simulation + Central Limit Theorem **25 days CPU time**

- Artificial Neural Network (ANN) surrogate model under development able to reproduce the JRODOS quality dispersion maps in a fraction of the time

O. Murat, et al., 2025, https://doi.org/10.1016/j.anucene.2025.111277
O. Murat, et al., 2026, ERMSAR

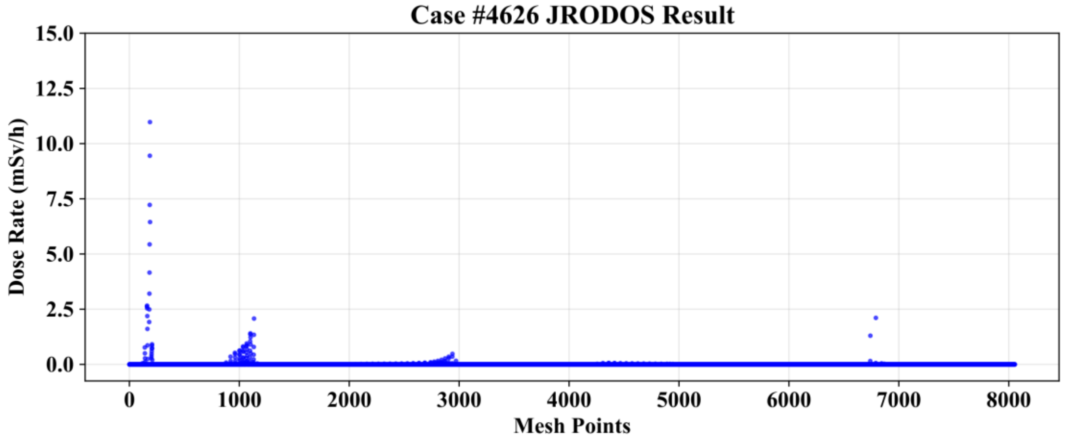
(courtesy of O. Murat)

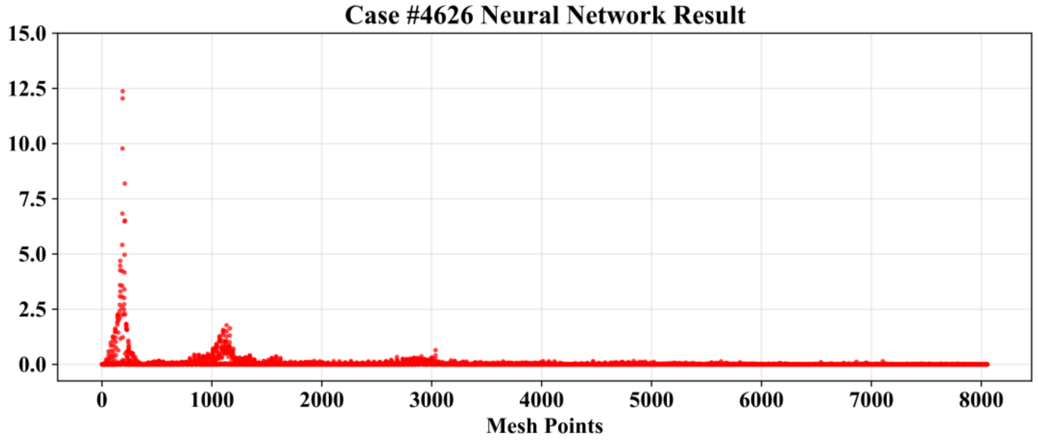
Reactor Physics and Dynamic

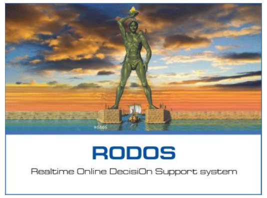
Rapid Prediction of Atmospheric Radioisotope Dispersion
Artificial Neural Network (ANN) Surrogate Approach

(courtesy of O. Murat)

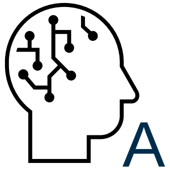
- **1,000 JRODOS simulations** was generated using a fictitious NPP location at KIT Campus North.
  - 100 km radius
  - **30 minutes time-steps over 24 hours simulation windows**
  - **Random sampling weather conditions (wind, T, P) of analysis starting time in year 2021**







~135 seconds



ANN

~0.08 seconds

The ANN model successfully identifies the spatial location and general footprint of the plume across the majority of test cases.

O. Murat, et al., 2025, https://doi.org/10.1016/j.anucene.2025.111277
O. Murat, et al., 2026, ERMSAR

Reactor Physics and Dynamic

(courtesy of S. S. Ottenburger)

JRODOS: AI & Simulation for optimized measures
Towards AI-powered Decision Support

RRADEW (2024-2026)

KIT/ITES-RESIS: **first prototype for AI-based decision support** for optimized preparedness measures by summer 2026, coupling **JRODOS** with **FRAMESS (Framework for Systemic Risk Analysis and Exploring Sustainable Solutions)** to enable faster, uncertainty-aware assessments and more effective protective-action planning

RRADEW

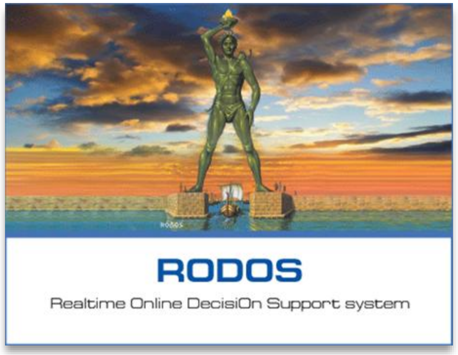
CITHARA (2026-2029)

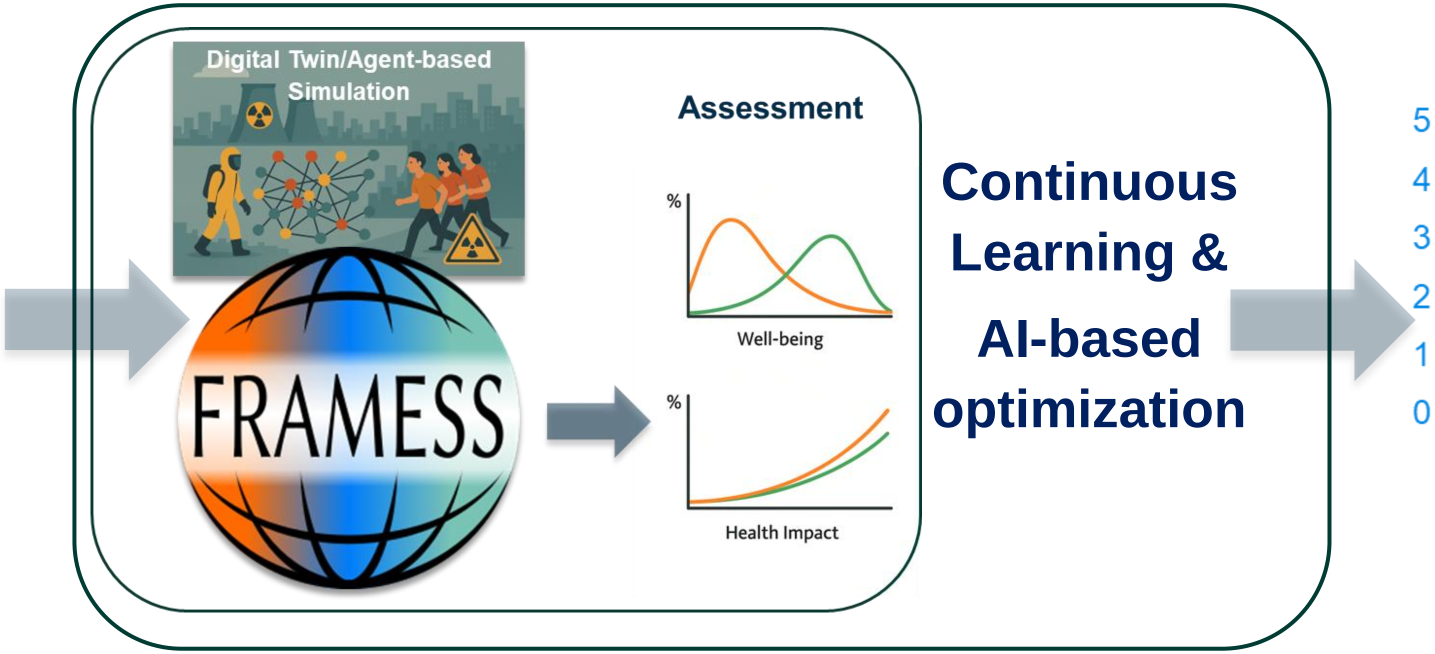
KIT/ITES-RESIS develops **AI-powered emergency-management** decision support system by coupling JRODOS with FRAMESS to **optimize protective actions** in **complex urban scenarios**

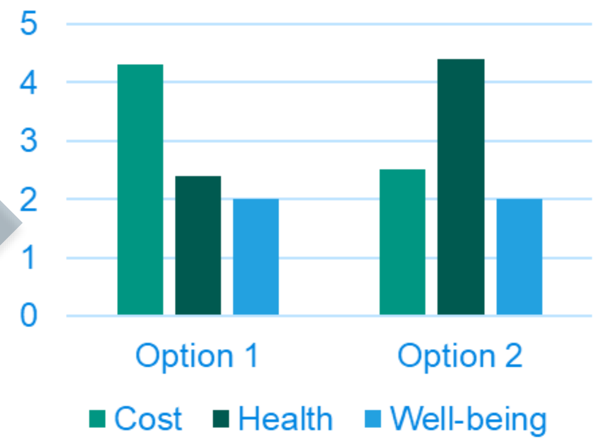
CIThARA

(courtesy of S. S. Ottenburger)

JRODOS: AI & Simulation for optimized measures
Methodology applied in RRADEW & CITHARA



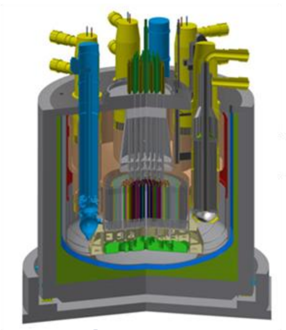




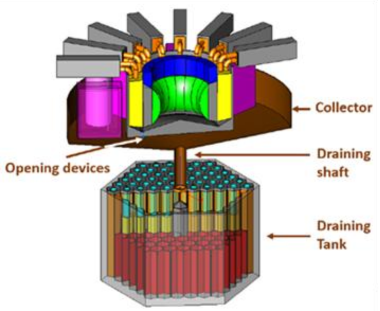
- **Preparedness Measures:** Infrastructure, Transport Means, Resources, Organization, Shelter…
- **Emergency Management & Early Countermeasures:** Sheltering, Evacuation, Iodine…

Advanced Nuclear Reactors' Safety

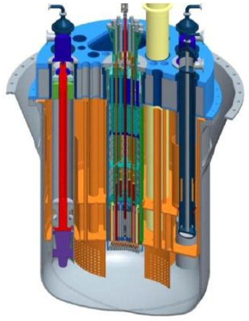
Large-Scale Facilities and Calculation Platform



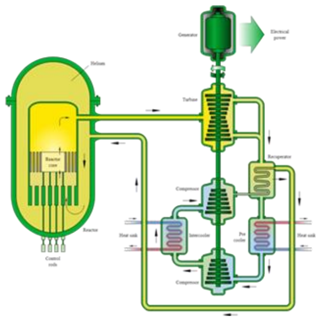
SFR



MSR



MYRRHA



GFR

Liquid Metal Thermal Hydraulics and Materials Research

Mission and Strategy

(courtesy of K. Litfin, A. Weisenburger)

We provide essential benchmark and reference data for **CFD codes, system codes and licensing tools** used **for liquid metal cooled nuclear systems** to the **interna-tional scientific community.**

Comprehensive investigations of **liquid metal ...**

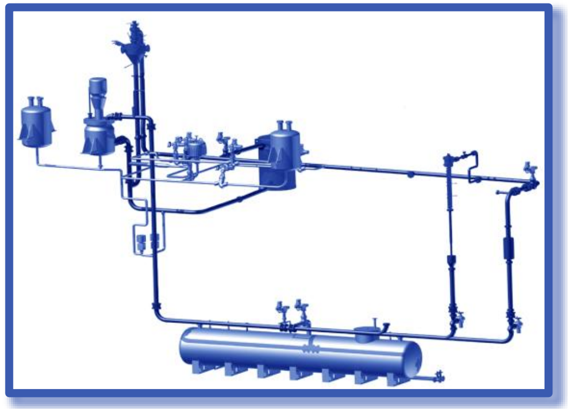
- **thermal hydraulics** in fuel bundles …
  - heat transfer
  - pressure losses
- **… with increasing compexity and fidelity …**
  - blockages, deformations
  - inter wrapper flow
- **… and including effects on structural material**
  - corrosion
  - degradation

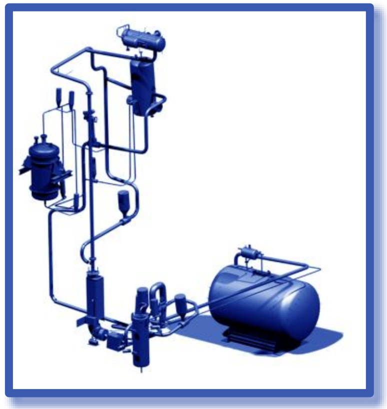
Liquid Metal Thermal Hydraulics and Materials Research
Strategic Foundations: Infrastructure and Scientific Program

(courtesy of K. Litfin, A. Weisenburger)

Loop facilities

- THEADES
- THESYS
- KASOLA

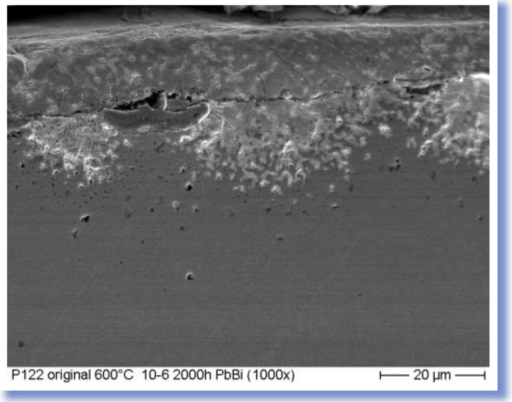




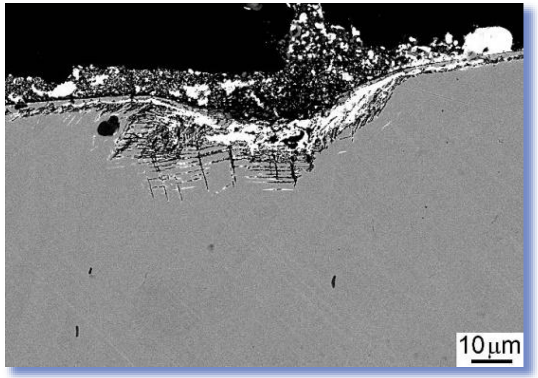
Worldwide uniqe facilities, leading contributor to the international liquid metal technology community.

Material test facilities

- Corrosion, erosion, degradation of mechanical properties
- Thermal stability and high temperature strength



P122 – 600°C
2000h



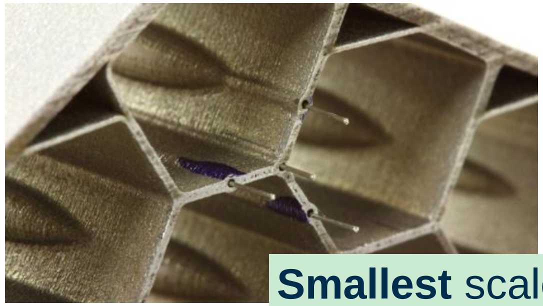
316l – 400°C
4000h

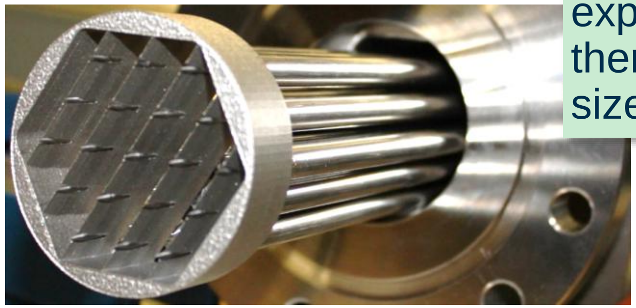
Example established Infrastructure Thermal Hydraulics

THEADES loop at Karlsruhe Liquid Metal Lab KALLA

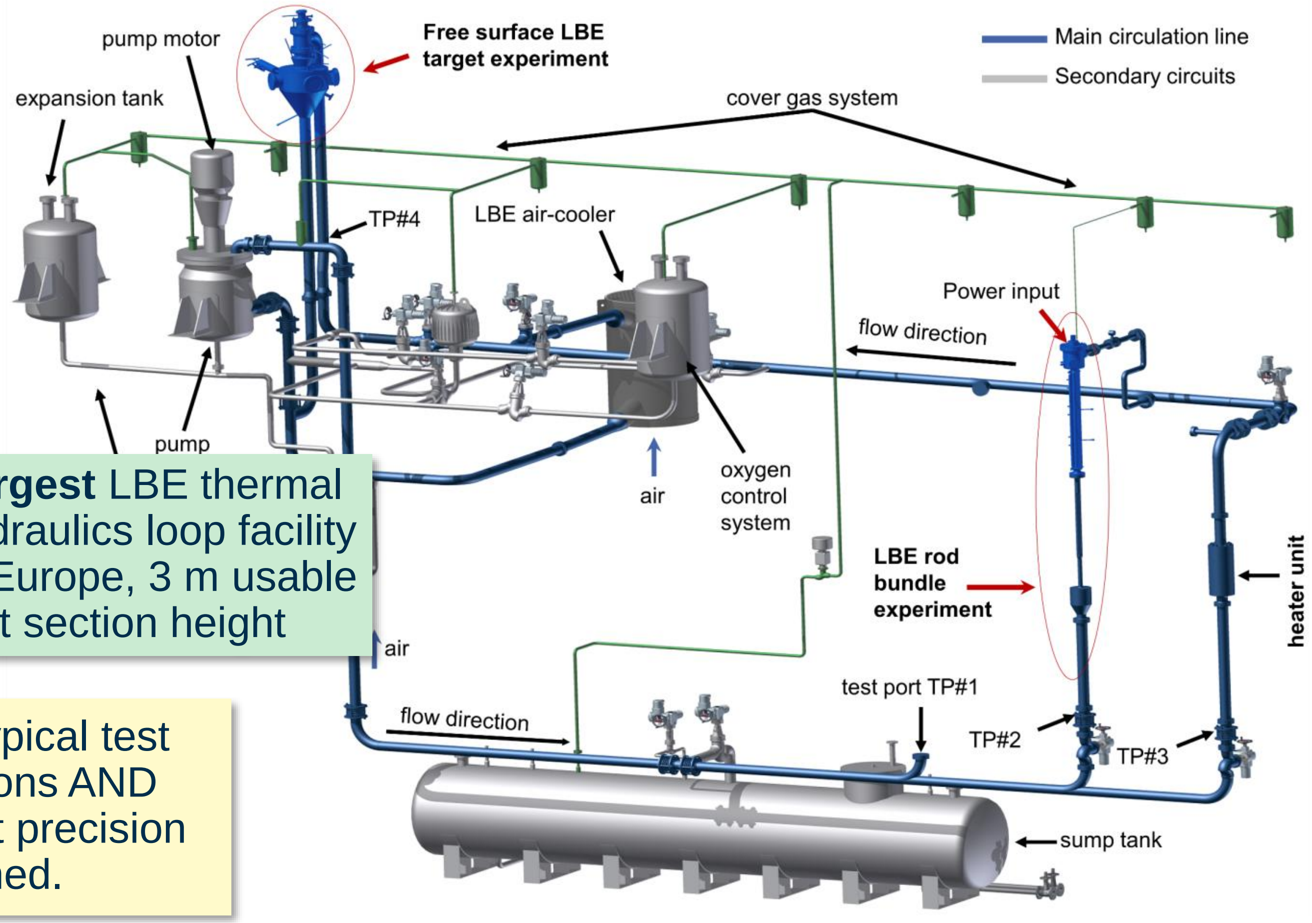
(courtesy of K. Litfin, A. Weisenburger)

- Inventory: 44 t Lead Bismuth Eutectic (LBE)
- Temperature: 180°C - 450°C
- Flow rate: 47 m^3/h (136 kg/s) max.
- Heating power: 500 kW max.





Smallest scale in experimental setup: thermocouple tip size 0.25 mm



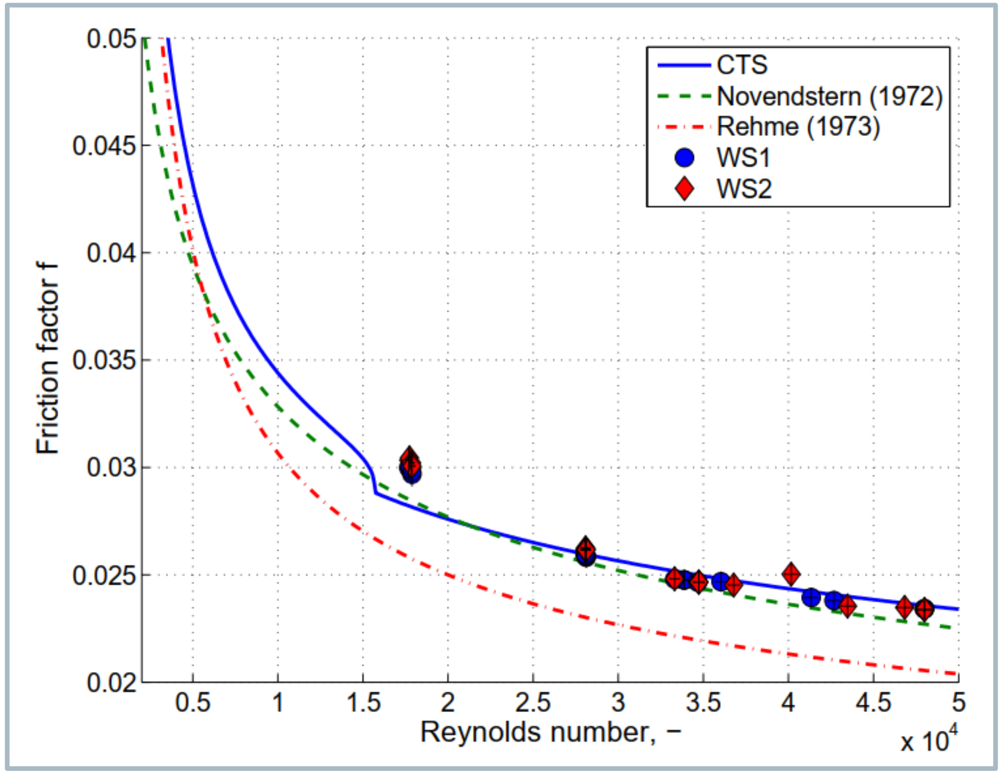
Largest LBE thermal hydraulics loop facility in Europe, 3 m usable test section height

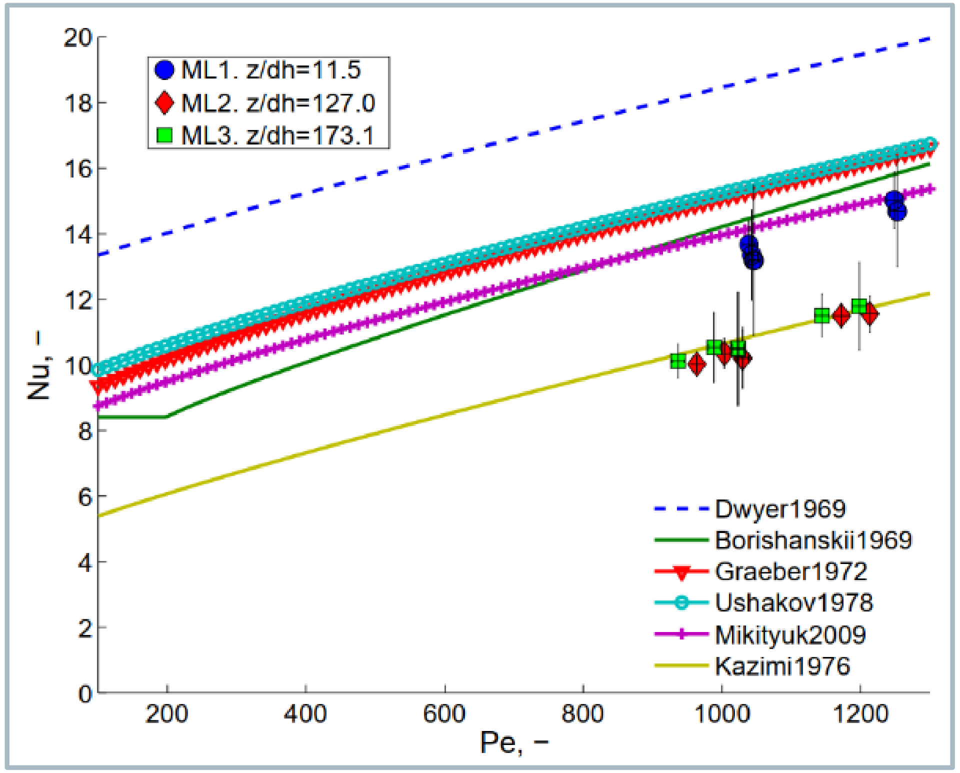
Prototypical test conditions AND highest precision combined.

Example Scientific Program - Thermal hydraulics
Highlight: Wire wrapped 19 pin bundle in LBE

Most conservative heat transfer correlation recom-mended for the MYRRHA safety assessment

Friction coefficient and Nusselt Number – Test and provision of correlations





J. Pacio et al., Technical Report MAXSIMA Deliverable D3.4
J. Pacio et al., NED, https://doi.org/10.1016/j.nucengdes.2016.03.003
J. Pacio et al., NED, https://doi.org/10.1016/j.nucengdes.2018.01.034

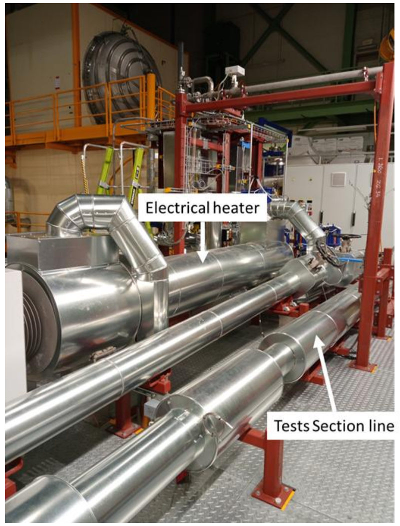
(courtesy of K. Litfin, A. Weisenburger)

(courtesy of S. Ruck, S. Perez-Martin)

Large Scale Facilities for Sodium-Cooled and MSR

Karlsruhe Sodium Lab

- Inventory: 7 m³ Sodium
- Operational since: **July 2024**
- Versatile research platform: **fundamental TH flow phenomena**, qualification of instrumentation, up to **prototypical component testing** e.g. for AMR and SFR



HELOKA-US

- Commissioned in **July 2025**
- Fluid: HITEC eutectic mixture of potassium nitrate, sodium nitrite and sodium nitrate (KNO_3 (53%), $NaNO_2$ (40%) and $NaNO_3$ (7%)
- Dimensionless numbers in the relevant range

- See, S. Perez-Martin, *The KIT Large-Scale Facilities and Computational Platforms Supporting Sodium-Cooled and MSR Systems*, Technical Session 3 – Severe Accident Codes & Experiments

Scientific Program Thermal Hydraulics AND Materials

Outreach and international collaboration

- OECD-NEA Expert Group on Reactor Coolants / Components Technology (EGCoCoT)
- IAEA-LMFNS Facilities Database
- IAEA Coordinated Research Projects
- IAEA Network for Experiments and code validation sharing (NEXSHARE)
- IAEA CRCP/SOD/003 978-92-0-104824-0

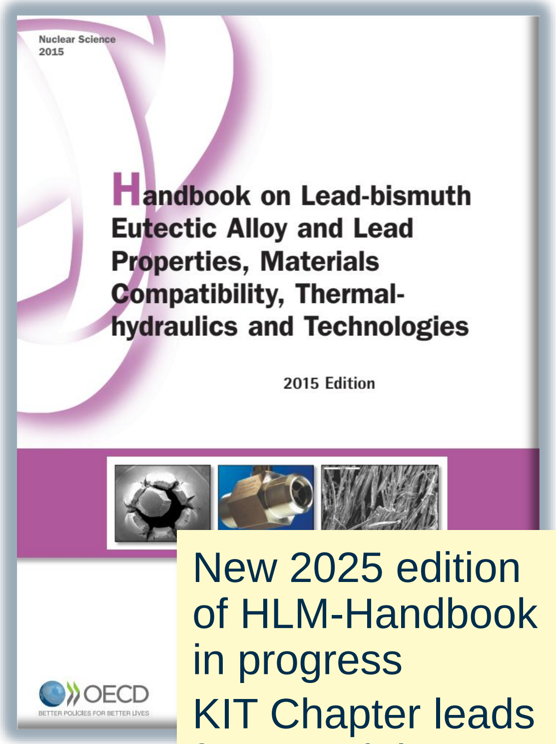
MAXSIMA

Transparant

PASCAL

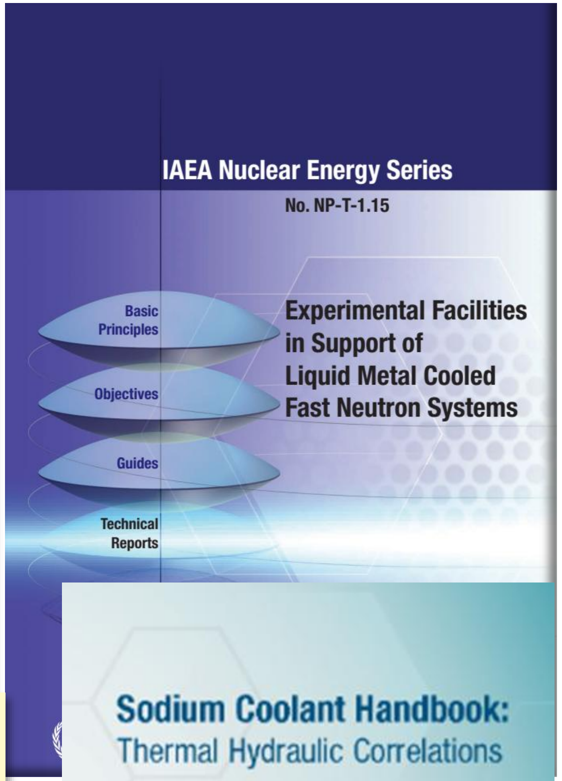
SEARCH

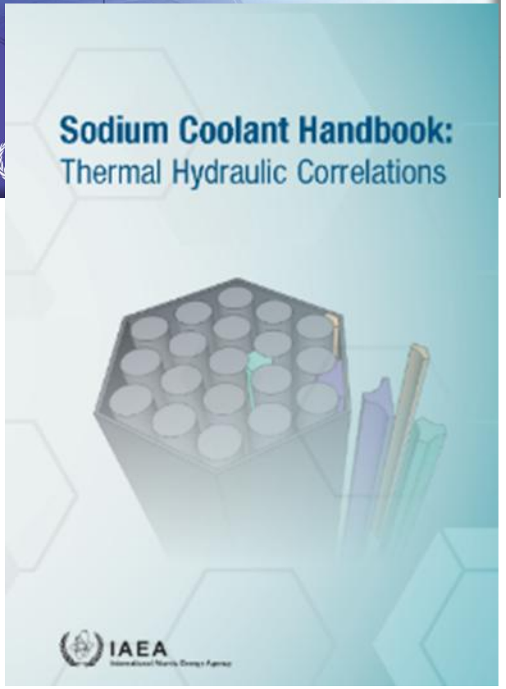
PATRICIA



New 2025 edition of HLM-Handbook in progress

KIT Chapter leads for materials, corrosion and instrumentation





OECD Publication: Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies – 2015 Edition
IAEA Publication: Experimental Facilities in Support of Liquid Metal Cooled Fast Neutron Systems
IAEA Publication: Sodium Coolant Handbook: Thermal Hydraulic Correlations, CRCP/SOD/003 978-92-0-104824-0

(courtesy of Perez-Martin)

Calculation Platform for Advanced Systems

	SFR	MSR	LFR	GFR
Exp. Facilities	**KASOLA, DITEFA**	**HELOKA-US**	**KALLA**	**AEROLAS**
Codes	SAS-SFR, SIM-SFR, SIMMER, CONTAIN-LMR	SIM-MS, SIMMER	SAS-LFR, SIM-LFR, SIMMER	SIM-GFR
Projects	EU ESFR-SIMPLE	EU SAMOFER	ANSELMUS, MYRRHA	TREASURE, IAEA S-allegro

- **SFR** - Code development and application
- Initiation phase of accidental transients → **SAS-SFR, SIM-SFR**
- Transition and Expansion phase of accidental transients → **SIMMER**
- Source term evaluation → **CONTAIN-LMR Code**

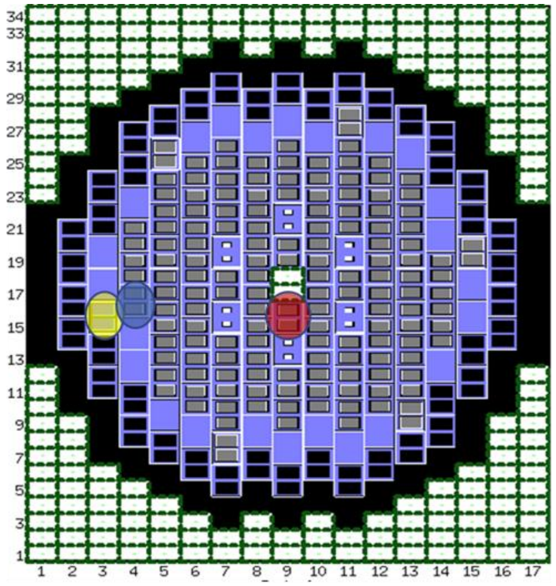
- See, S. Perez-Martin, *The KIT Large-Scale Facilities and Computational Platforms Supporting Sodium-Cooled and MSR Systems*, Technical Session 3 – Severe Accident Codes & Experiments

MYRRHA-Lead Fast Reactor

(courtesy of A. Rineiski)

Highlight: 3D SIMMER Capability for Transient Analyses

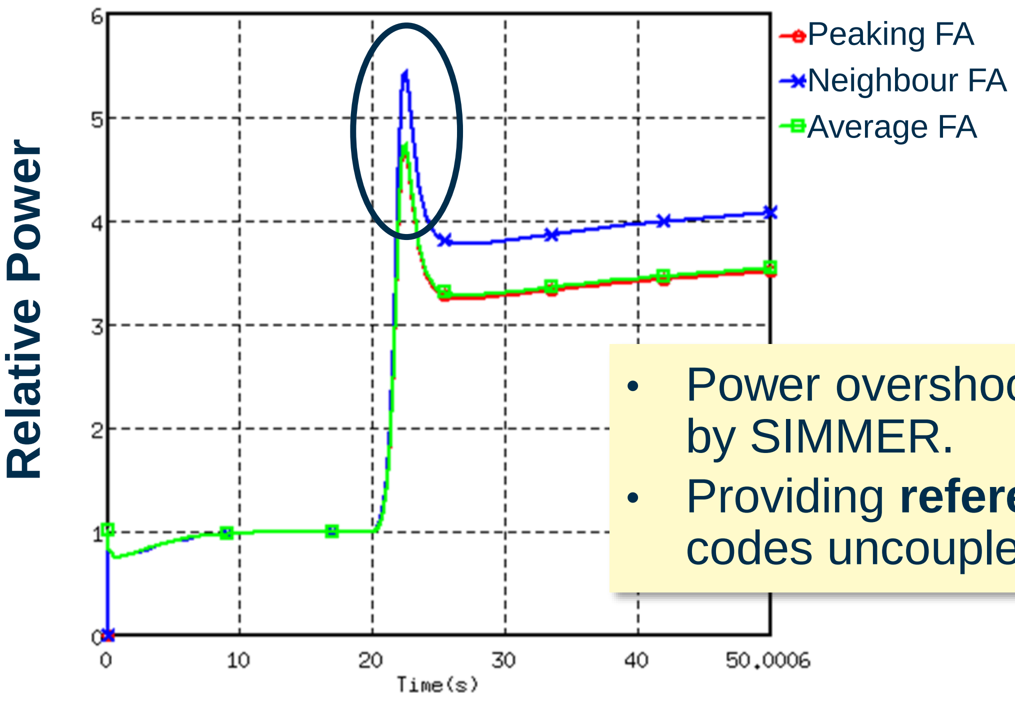
- Supporting the validation of codes applied for Lead Fast Reactor licensing, such as RELAP
- **3-D neutronics & fluid-dynamics coupled calculation** of a Control Rod withdraw transient



CR withdrawn

CR Neighboring FA

Peak Power Fuel Assembly (FA)



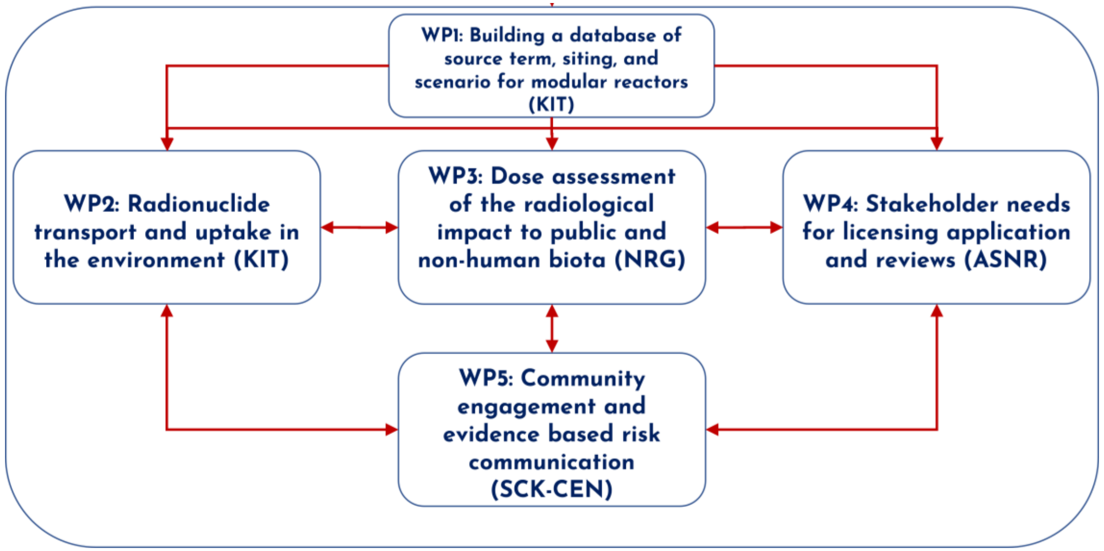
ANSELMUS

- Power overshooting (15%) computed by SIMMER.
- Providing **reference solutions** to TH codes uncoupled with neutronics.

EIA and EP&R for AMRs

The CATAPULT Project

- **Comprehensive AssessmenT And Preparedness for emerging nUcLear Technologies**
- Scope: building a **comprehensive guidance to all stakeholders for EIA and EP&R** applied to SMRs and **AMRs (Gas- and Lead-cooled**) with tight cross-links between technical and social aspects
- Cross-fertilization of a highly interdisciplinary team tailored to **develop a fit-for purpose framework on EIA modelling, regulatory compliance, and engagement with the community**



https://pianoforte-partnership.eu/catapult/

The CATAPULT Project
Pillars and Main Goals

- **Environmental and dose modelling for SMRs and AMRs**
  - **Improving/adapting** the **dose** impact and the **environmental transport models**
  - Outcome: **analysis computational framework for EIA and EP&R tailored** to the needs of modular reactors and **their typical site locations**

- **Science-based regulatory compliance for SMRs and AMRs**
  - Outcome: **comprehensive set of recommendations to authorities, operators, and licensees** ensuring the demonstration of radiation protection of public and environment

- **Community Engagement & Risk communication for novel nuclear technologies**
  - Outcome: **community-driven participatory framework towards a more holistic EIA**
  - Outcome: **guidelines to communicate EIA results and inform the public** about SMRs and AMRs development/implementation → evidence-based **co-design of risk communication strategy**

https://pianoforte-partnership.eu/catapult/

Summary

- **Preserving, extending, and sharing the knowledge regarding reactor safety, EIA, and EP&R for current and advanced nuclear NPPs**
- Large scale **Experimental Platform** and extend to new materials and safety-relevant phenomena of innovative reactors
  - **Providing worldwide recognized, independent, high quality reference data and know-how** on water cooled and liquid metal thermal hydraulics and material research
- Extending the **Computational Platform** for innovative reactors, new materials, AI/ML
  - **Providing beyond state-of-the-art calculation methods for safety analysis, EIA and EP&R**
- Enhancing the **synergy** among the KIT experimental and computational platforms
  - **KIT as 'full' package provider of data and know-how** to support code developers and to widen the range of application of codes
- **Keep active role in the international community**, e.g., EU research programs and strategic cooperation with leading international institutions

Reactor Physics and Dynamic

Acknowledgement

- NUSAFE Program: W. Tromm
- QUENCH: J. Stuckert, M. Große, M. Steinbrück, D. Bachurina, D. A. Schäfer, C. Rössger (https://quench.forschung.kit.edu/)
- COSMOS: S. Gabriel, W. Heiler, N. Wefers (https://www.ites.kit.edu/675.php)
- KALLA: K. Litfin, A. Weisenburger (https://www.ites.kit.edu/english/140.php)
- KASOLA, HELOKA-US: S. Ruck, S. Perez-Martin (https://www.inr.kit.edu/58.php)
- Computation Advanced NPPs: A. Rineiski, B. Kędzierska, Y. Tobita, X. N. Chen, L. Marzullo (https://www.inr.kit.edu/english/967.php)
- JRODOS: S. S. Ottenburger, W. Raskob, D. Trybushnyi (https://www.ites.kit.edu/136.php)
- Computation Water-cooled NPPs: V. H. Sanchez-Espinoza, M. E. Cazado, A. Campos Munoz, J. Duran Gonzalez, G. Huaccho Zavala, Z. Jimenez Balbuena, I. Karaaslan, L. Mercatali, O. Murat, Y. Song, A. Stakhanova, S. Wang, K. Zhang, F. Kretzschmar (https://www.inr.kit.edu/342.php, https://www.multiphysics.kit.edu/)
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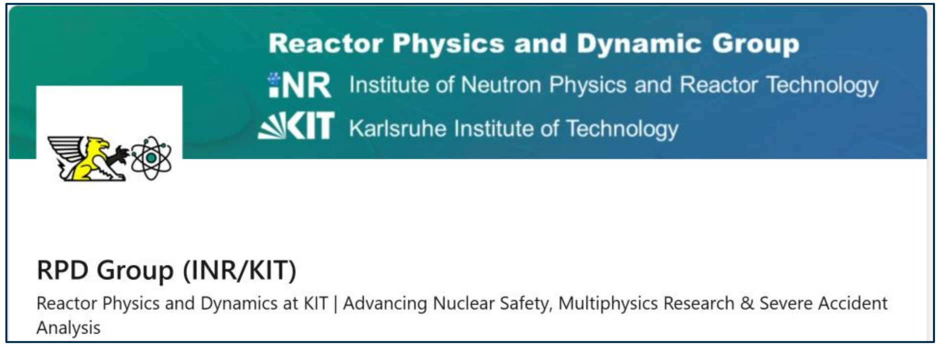
- KALLA https://www.ites.kit.edu/english/140.php
- KASOLA, HELOKA-US https://www.inr.kit.edu/58.php
- Computation Advanced NPPs – INR/ADE https://www.inr.kit.edu/english/967.php
- JRODOS https://www.ites.kit.edu/136.php
- Computation Water-cooled NPPs – INR/RPD https://www.inr.kit.edu/342.php
- KIT Scientific Computing Center (SCC) https://www.scc.kit.edu/

https://www.multiphysics.kit.edu/

https://www.linkedin.com/company/rpd-group-inr-kit



The Helmholtz Association

Germany‘s Largest Research Organization

- 43,000 employees
- Annual budget of ≈ 5 billion euros
- 18 Helmholtz Centers

KIT participation in 11 programs of 4 Helmholtz Research Fields with a funding volume of 338 million euros per year (as of 2024)

Helmholtz Research Fields

Energy	Earth & Environment	Health
Aeronautics, Space and Transport	Information	Matter

This makes KIT and Helmholtz unique partners with common goals.