Karlsruhe Institute of Technology

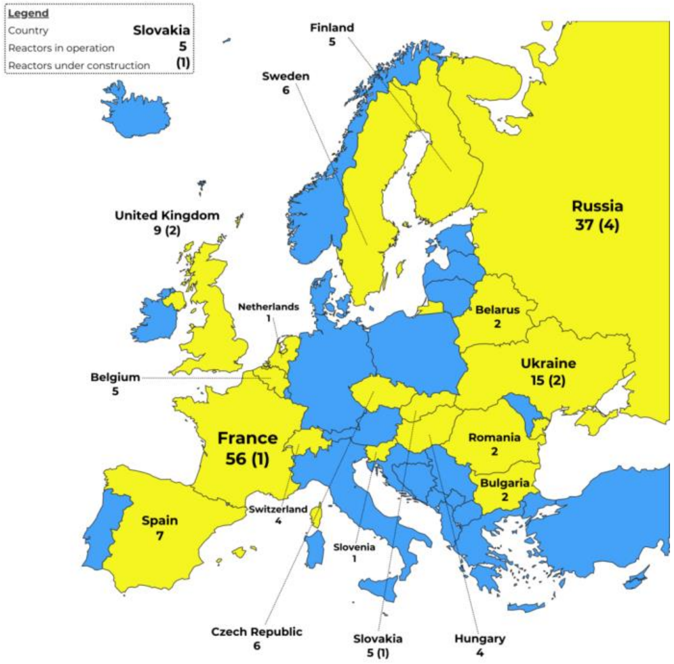
Overview and Outlook of the Computational Activities at KIT for the Safety Assessment and the Radiological Risk Prediction of Nuclear Power Plants

F. Gabrielli, V. H. Sanchez-Espinoza

Institute for Neutron Physics and Reactor Technology

Motivation

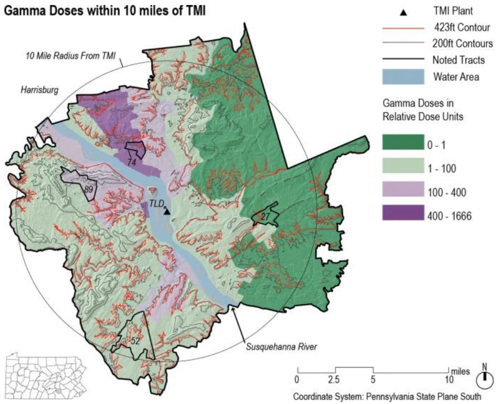
- <u>Many</u> and <u>different</u> NPPs under operation and going to be deployed around Germany and worldwide
- Hypothetical severe accidents with FP release cannot be excluded a priori (zero risk does not exist)
- **Keeping the expertise on methodologies to assess the hypothetical risk that may arise from the operation of NPPs** → one of the **HGF's mission**
- **Evaluation of the radiological consequences of hypothetical severe accidents** in current operating NPPs as well as in the innovative designs → one of the milestones of the **NUSAFE Program of KIT**

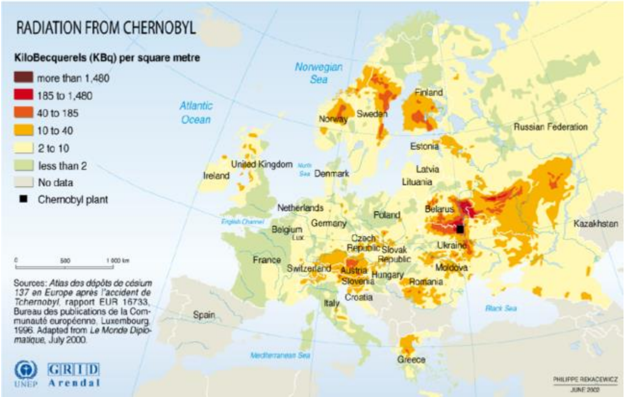


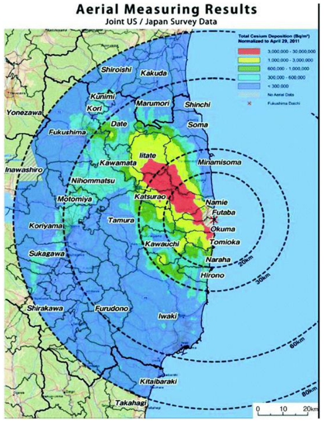
Situation at May 2023
https://www.euronuclear.org/glossary/nuclear-power-plants-in-europe/

Motivation

- National regulators want to know reliable data about expected radiological risk
- Mandatory: <u>Reliable</u> evaluations of the **radiological consequences** of hypothetical **severe accidents** in a NPP → Emergency Planning Zones (EPZ) → support the **emergency management** during such events <u>also in nuclear-free countries</u>
- **No national borders exist to the radiological impact of hypothetical severe accidents in a NPP**

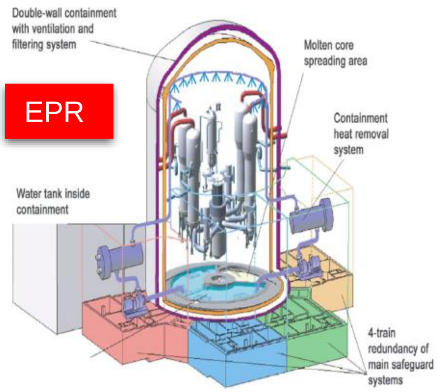


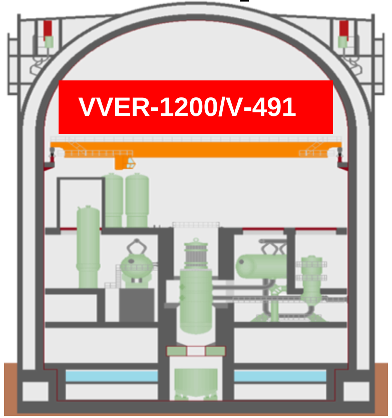


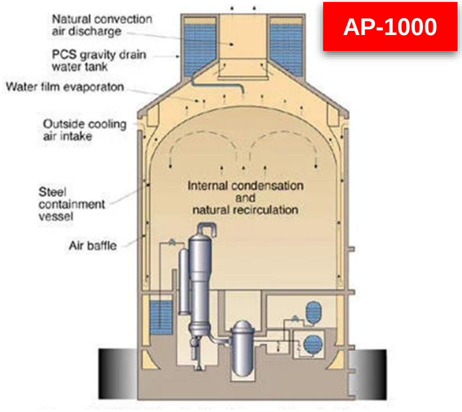


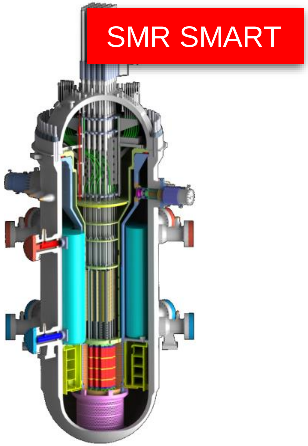
Datesman, A.M. Radiobiological shot noise explains Three Mile Island biodosimetry indicating nearly 1,000 mSv exposures. Sci Rep 10, 10933 (2020). https://doi.org/10.1038/s41598-020-67826-5
Nuclear Regulation Authority (2011) Results of airborne monitoring by the Ministry of Education, Culture, Sports, Science and Technology and the U.S. Department of Energy (in Japanese)

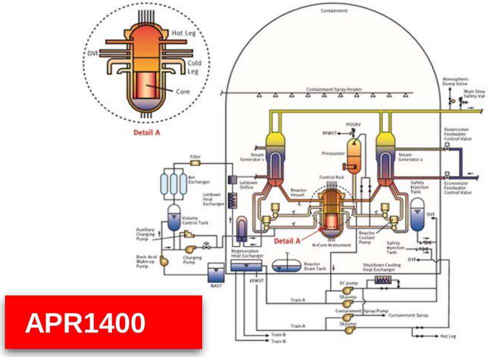
NPP Technology Developments: Drivers

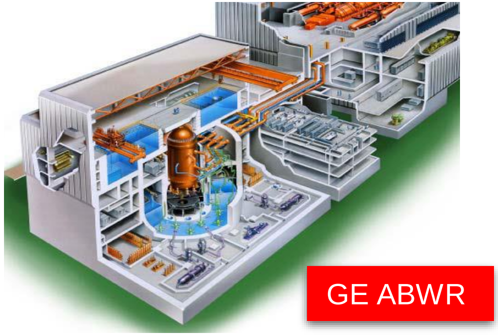


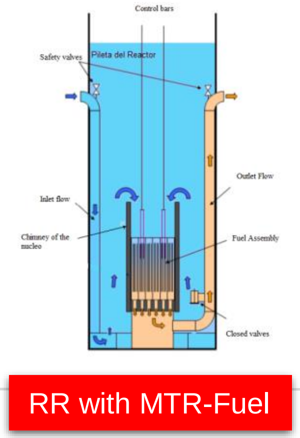


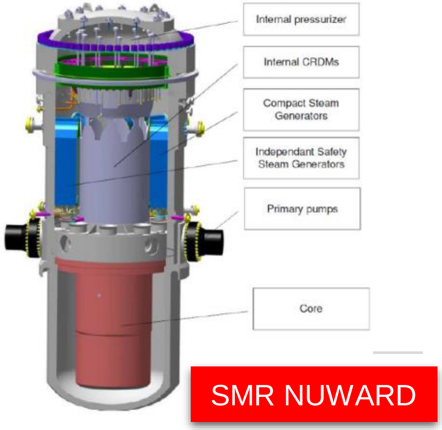










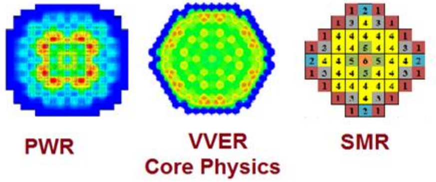


Reactor Physics and Dynamics (RPD) Group

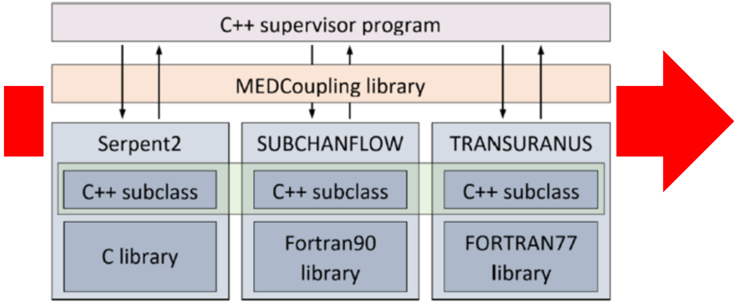
- Development, validation, and improvements of the calculation tools dealing with different physical domains of the nuclear reactor safety
- Combination of in-house and external codes embedded in international cooperations (USNRC CAMP, USNRC CSARP, KIT/IRSN strategic cooperation)
- Research areas
  - Multiphysics and multiscale approach to core and plant analyses (nominal operation and Design Basis Accidents)
  - Validation of codes using KIT and external experiments
  - Uncertainty and Sensitivity Analyses
  - Analysis of severe accidents in NPPs
  - Radiological consequences of severe accidents

Multi-physics (core) and -scale (plant) analyses

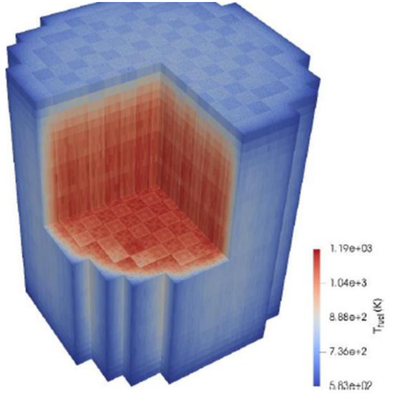
- Use of the thermal hydraulic solvers in regions of a nuclear power plant where their physical models and spatial resolution assure the best results
- Increasing the prediction accuracy, fidelity and spatial discretization of computational domains



Neutronics	Thermal hydraulics	Thermo-mechanics
- PARCS - PARAFISH - Serpent2	- TRACE - Subchanflow - Twoporflow	- Transuranus



Pin-by-pin core analysis



- plus…coupling Neutronics/TH/CFD codes – Multiscale analyses

KIT Multiphysics Analyses Current Framework

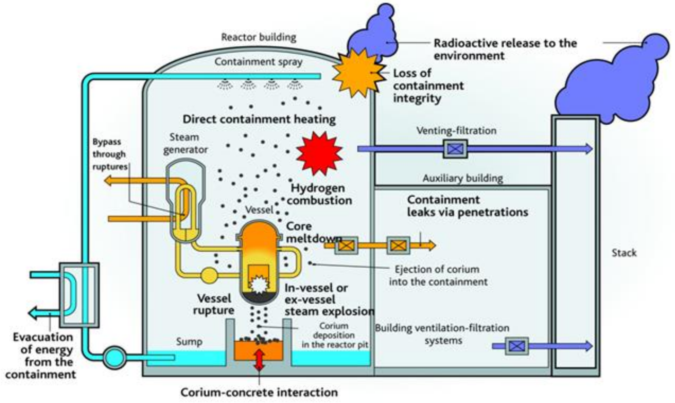
- **H2020 Project McSAFER (High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic Small Modular Reactors) (KIT/INR/RPD as coordinator) (www.mcsafer-h2020.eu)**
  - Advance safety research for Small Modular Reactors (SMR) by combining experimental investigations and innovative numerical simulations.

- **CAMIVVER (Codes and Methods Improvements for VVER Comprehensive Safety Assessment) (www.camivver-h2020.eu) (KIT/INR/RPD as WP Leader)**
  - Development and improvement codes (NT, TH, safety) and methods for VVER comprehensive safety assessment (Nominal and accidental conditions, validation)

Hypothetical Severe Accidents in LWRs: Overview

- Hypothetical severe Accidents in NPPs are generally triggered by a failure within the reactor cooling system and by multiple dysfunctions, including the failure of safety procedures → Namely, **no proper removal of residual power from the core occu**rs.

- ..may lead to large core degradation, failure of the safety barriers, and a massive release of fission products from the vessel to the containment and the environment.



- **Challenges:**
  - **Several non-linear phenomena occurring simultaneously**
  - **Accident progression and source term dependent on the kind of reactor, i.e. PWR, BWR, VVER,SMR, … and on the scenarios**

KIT Strategy for SA Analyses (basic route)

- Source Term (ST): *The types, quantities, and physical and chemical forms of the radionuclides present in a nuclear facility that have the potential to give rise to exposure to ionizing radiation, radioactive waste or discharges*.
- Step-wise calculation route:
  - **Status of the core when the SA occurs, i.e. burn-up (multiphysics analyses)**
  - **Analysis of the accident scenario (integral codes)**
    - FPs behavior during the in-vessel and ex-vessel phases
    - Source Term
  - **Dispersion in the environment (decision support system tools)**

KIT Strategy for SA Analyses (extended route)

- Source Term (ST): *The types, quantities, and physical and chemical forms of the radionuclides present in a nuclear facility that have the potential to give rise to exposure to ionizing radiation, radioactive waste or discharges*.
- Step-wise calculation route:
  - **Status of the core when the SA occurs, i.e. burn-up (multiphysics analyses)**
  - **Analysis of accident scenarios for different initiators (integral codes)**
    - FPs behavior during the in-vessel and ex-vessel phases
    - Source Term
  - **Uncertainty propagation and assessment of ST database (integral codes + UQ tools)**
  - **Uncertainty Quantification of the ST database (integral codes + UQ tools)**
  - ST prediction (integral codes + UQ tools + predictive algorithms)
  - **Dispersion in the environment (decision support system tools)**

KIT Strategy for SA Analyses - Codes

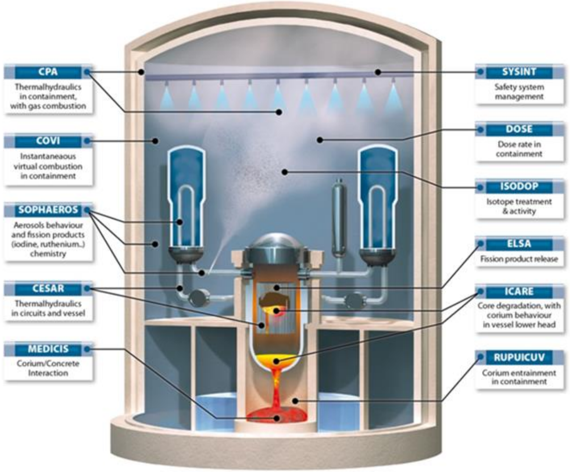
- **Combination and improvement of in-house and foreign codes**
  - **Evaluation of the fuel inventories** (CASMO,SCALE/ORIGEN,KORIGEN)
  - **Severe Accident analyses and source term evaluation**
    - **ASTEC (KIT/IRSN agreement, KIT as co-developer)**
    - **MELCOR (USNRC/KIT Cooperative Programs CSARP and MCAP)**
  - **Uncertainty and sensitivity analysis → training database of ST from integral codes**
    - KArlsruhe Tool for Uncertanty and Sensitivity Analyses (**KATUSA, in-house**)
    - Fast Source Term Code (**FSTC, in-house**) → ST prediction → Bayesian Network Algorithms
  - **Radiological consequences of FP release in the environment**
    - Java Real-time On-line Decision Support System (**JRODOS, KIT/ITES**)

The ASTEC Code

Karlsruhe Institute of Technology

- **ASTEC (Accident Source Term Evaluation Code)** developed by IRSN since 1996 to **analyze the complete SA scenario from the initiating event until radioactive release out of the containment in Gen. II and Gen III water-cooled reactors**.

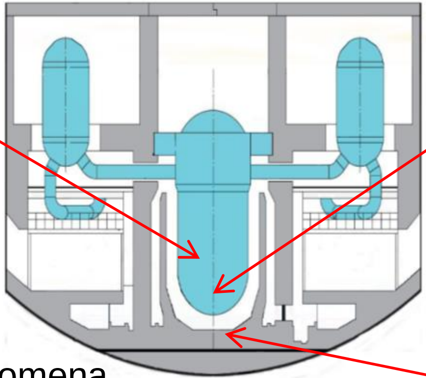
- **KIT supporting the code development since 2020 (KIT-IRSN License Agreement).**
- **Code validation against KIT and foreign experiments**
- **KIT as unique and excellent multi-science environment**



Large scale test facilities at KIT

Core coolability and debris cooling

QUENCH

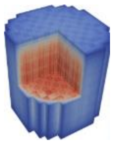


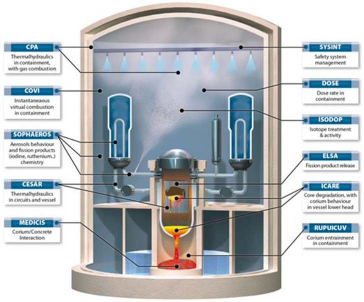
MOCKA

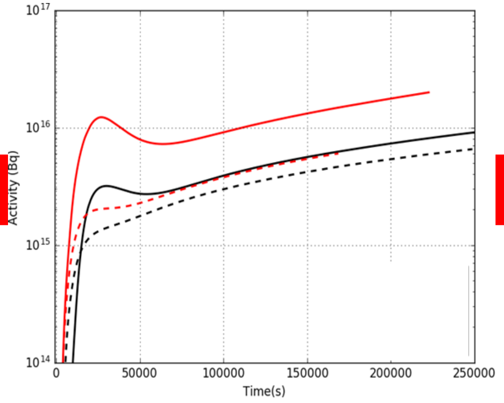
MCCI

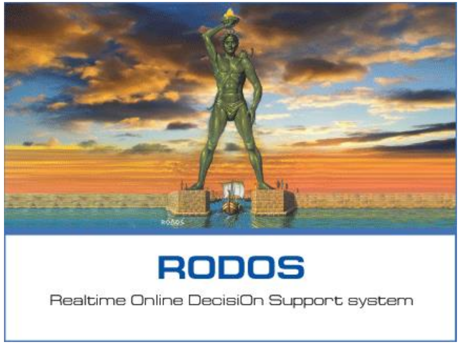
Containment phenomena

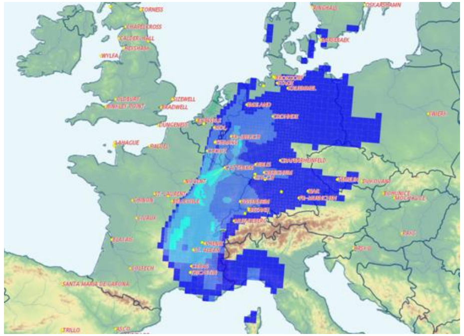
KIT calculation Platform (basic route)





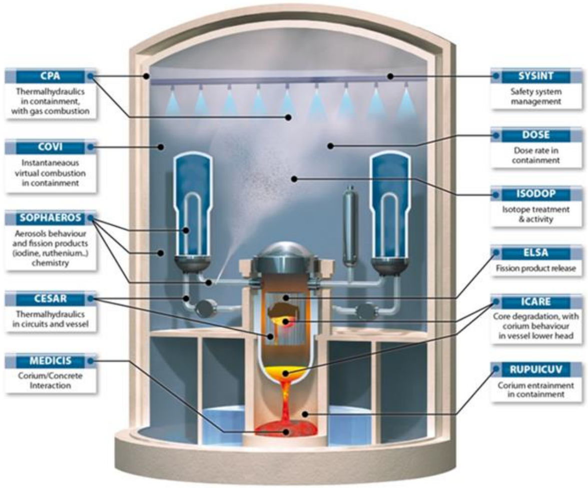




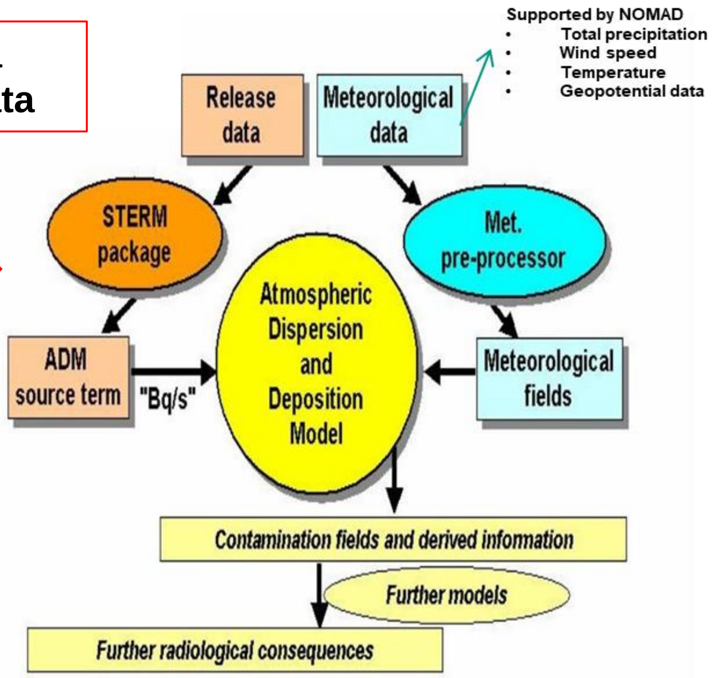


- **Complete calculation chain from fuel inventory evaluation to the analysis of FPs dispersion in the environment**

The ASTEC/JRODOS Platform



- Isotope-wise mass data
- Isotope-wise activity data



➢ ASTEC/JRODOS coupling assessed at INR → **first-of-its-kind**

W. Raskob, 2012. Radiological consequences to the environment resulting from Severe Accidents, Course on Severe Accident Phenomenology and Management, KIT, July 10th -11th.

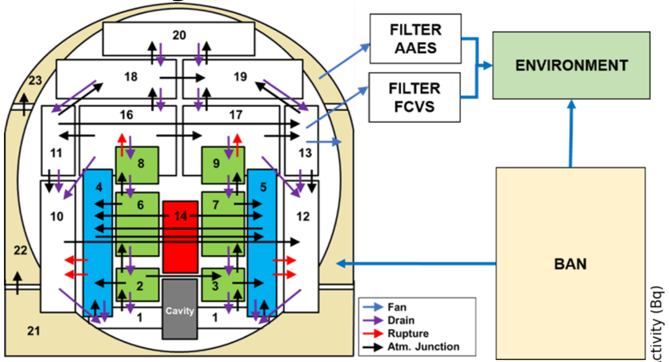
KIT SA Analyses Current Framework (1/2)

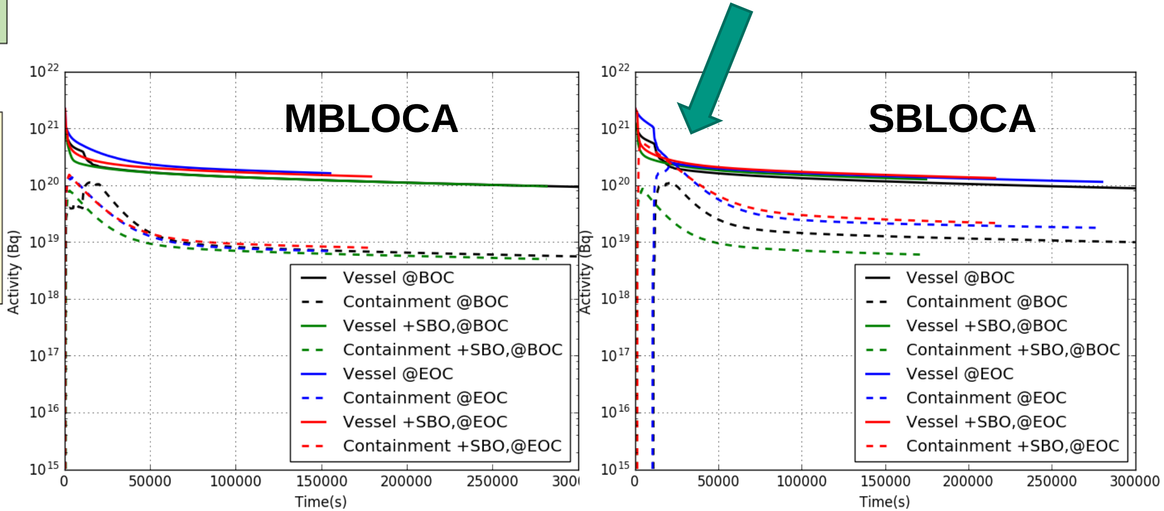
- **EU Management and Uncertainties of Severe Accidents (MUSA) Project** (2019-2023) **(KIT/INR/RPD WP Leader, KIT/Framatome GmbH joint contribution)**
  - Assessing the capability of **SA codes** when modelling SA scenarios for Gen. II/III/III+ reactor designs and SFPs by using the **UQ methods**.
- **EU Safety Analysis of SMR with PAssive Mitigation strategies - Severe Accident (SASPAM-SA) Project (2022-2026) (KIT/INR/RPD WP Leader)**
  - Hypothetical severe accident analyses of **Integral Pressurized Water Reactor (iPWR), Emergency Planning Zone (EPZ)**, European licensing analyses needs
- **EU SEvere Accident Research and Knowledge ManagemenT (SEAKNOT) Project (2022-2026) (KIT/INR/RPD WP Leader)**
  - Shaping up a **roadmap for severe accident research to reduce the remaining uncertainties** and measurable progress in the practical elimination of radiological consequences.

KIT SA Analyses Current Framework (2/2)

- **EU Artificial intelligence for the Simulation of Severe AccidentS (ASSAS) Project (2022-2026) (KIT/INR/RPD WP Leader)**
  - First-of-its-kind extensive use of **AI algorithms for developing fast-running surrogate models for severe accident modelling**
- **IAEA CRP I31033 on U&S Methods for SA Analysis in Water Cooled Reactors** (2019-2024) **(KIT/INR/RPD CRP Chair)**
- **OECD/NEA QUENCH-ATF Project** (2021-2024) **(KIT as Coordinator)**
- **IAEA CRP T12032 'Testing and Simulation for Advanced Technology and Accident Tolerant Fuels' (ATF-TS)** (2019-2024)

Activity in the Vessel and in the Containment



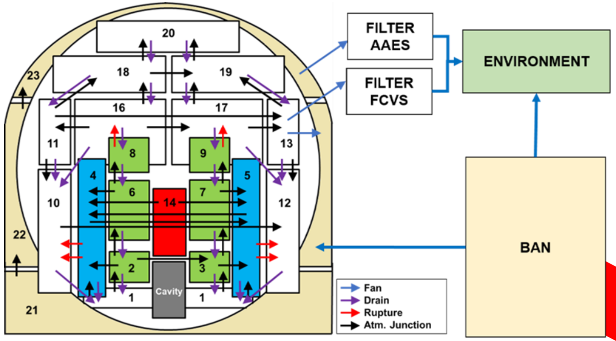


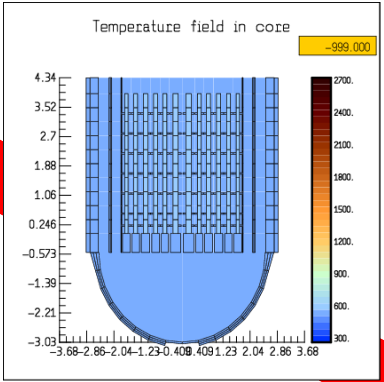
Initial Inventory			
Volatility	Element	BOC (Ci)	EOC (Ci)
Noble Gases	Xe	4.06E+08	4.53E+08
	Kr	1.17E+08	1.24E+08
Very Volatile	I	1.16E+09	1.28E+09
	Cs	1.00E+09	2.08E+10
Moderately Volatile	Te	6.10E+08	6.88E+08
	Sr	2.98E+08	3.76E+08
	Ba	1.48E+10	1.87E+10
Less Volatile	Ru	3.50E+08	4.16E+08
	La	6.04E+08	6.66E+08
	Ce	4.49E+08	5.12E+08

- Significant amount of the activity in the vessel transported to the containment.
- Effect of the a different inventory and scenario looks the dominant.

Example of Application (PWR KONVOI NPP)

- ASTEC model of a generic KONVOI NPP
- Scenario MBLOCA (12” on the cold leg)

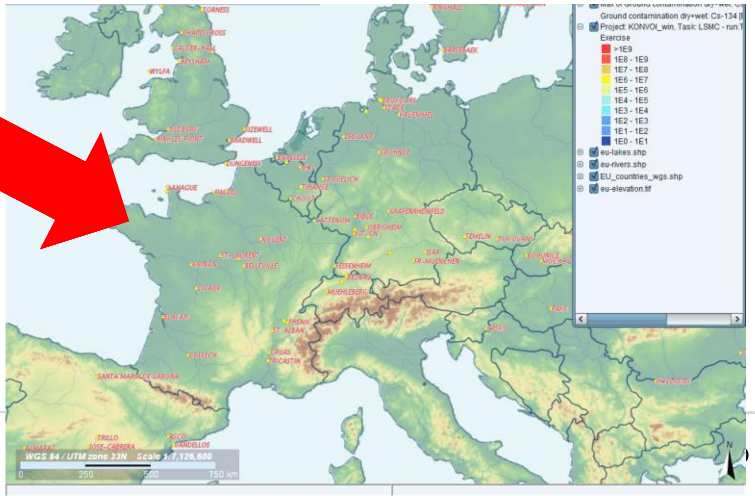




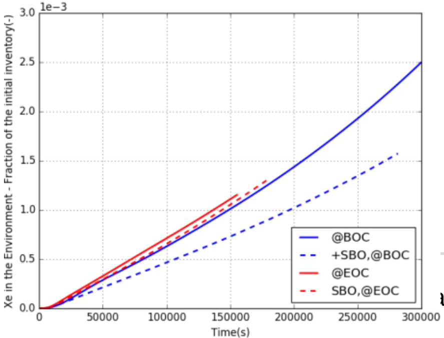
Cattenon site (France)

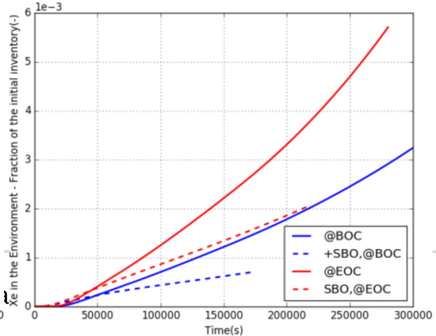
Radiological consequences:

Cs134 contamination (winter time)



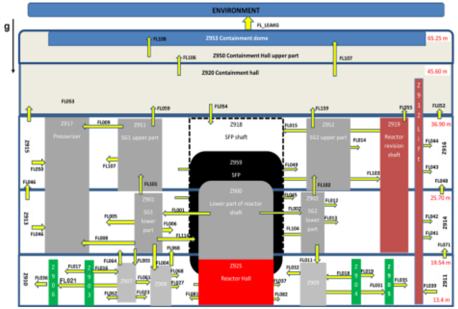
Xe release to the environement





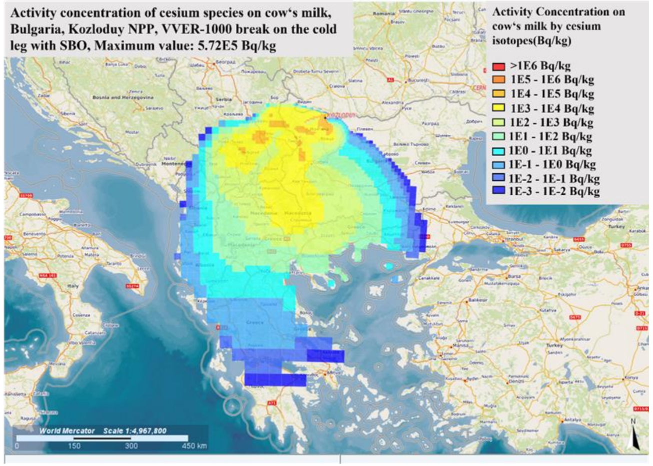
VVER-1000 abd BWR Mark-I applications

➢ VVER-1000 (SBO+LBLOCA)



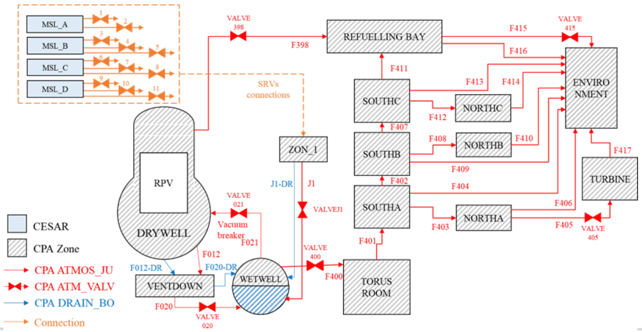
Kozloduy NPP

Activity concentration of Cs species on cow's milk

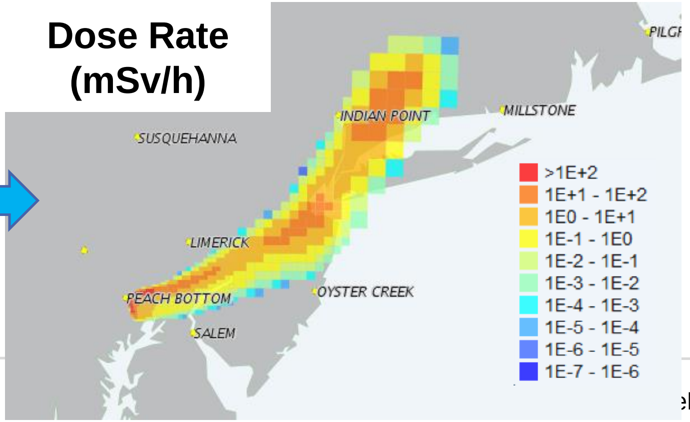


K. Mercan, F. Gabrielli, V. H. Sanchez-Espinoza and W. Raskob, 2022, "Analysis of the consequences of a LBLOCA with SBO severe accident in a generic VVER-1000 by means of ASTEC and JRODOS codes," Nuclear Engineering and Design, vol. 400, p. 112078, 2022.

➢ BWR Mark-I (Peach Bottom) (SBO)



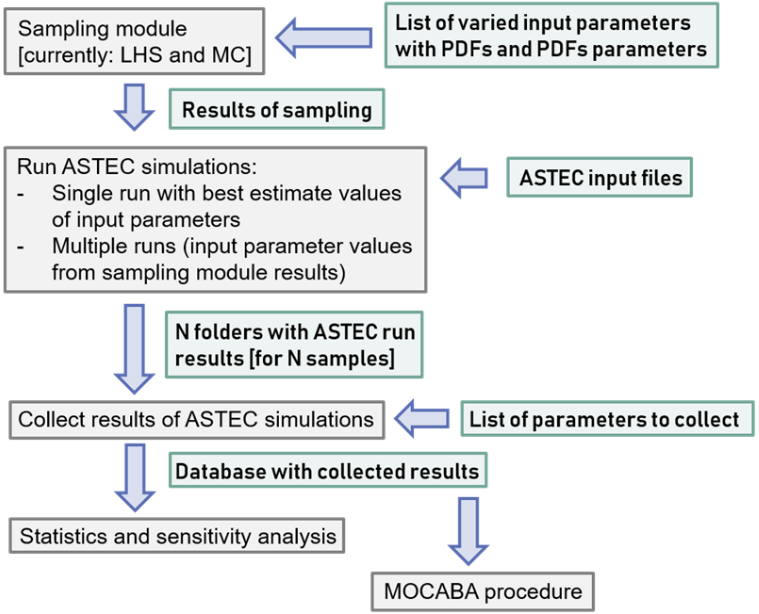
Dose Rate (mSv/h)



Murat, O., Sanchez-Espinoza, V., Gabrielli, F., Stieglitz, R., and Queral, C., "Analysis of the Short Term-Station Blackout Accident at the Peach Bottom Unit-2 Reactor with ASTEC Including the Estimation of the Radiological Impact with JRODOS", Submitted to Nuclear Engineering and Design (under review)

The In-house KATUSA and FSTC codes

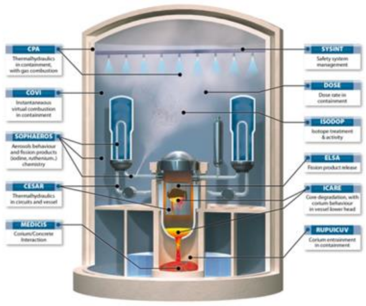
- **Source term evaluation affected by the uncertainties still existing on SAs modeling, i.e. MCCI.**
- Framework: EU MUSA and German WAME projects.
- KATUSA and FSTC tools developed at KIT
  - Python based
  - Easy to be installed on any machine and environment
  - Two 'modes': UQ and UQ+Prediction (FSTC)
  - Verified against URANIE



A. Stakhanova, et al., Uncertainty and sensitivity analysis of the QUENCH-08 experiment using the FSTC tool, Annals of Nuclear Energy, Annals of Nuclear Energy, 169, p.108968.
A. Stakhanova, et al., PRELIMINARY UNCERTAINTY AND SENSITIVITY ANALYSIS OF THE ASTEC SIMULATIONS RESULTS OF A MBLOCA SCENARIO AT A GENERIC KONVOI PLANT USING FSTC TOOL, Proc. of ERMSAR2022, 16-19 May 2022, Karlsruhe, Germany, DOI: 10.5445/IR/1000151444, https://publikationen.bibliothek.kit.edu/1000151444.

UQ of the ST during SAs

ASTEC Source Term Database
ASTEC/KATUSA



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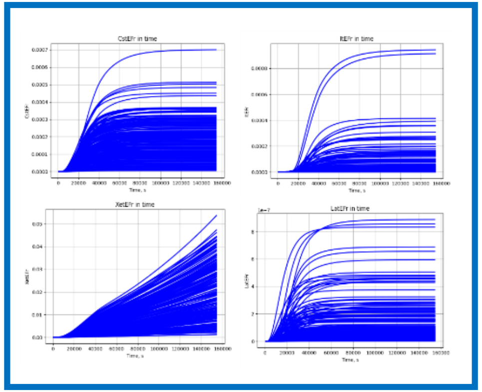
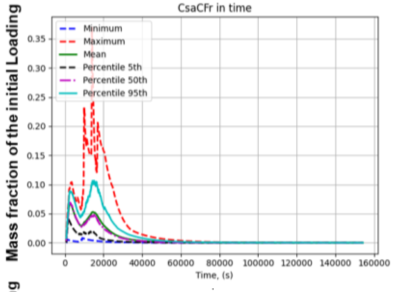
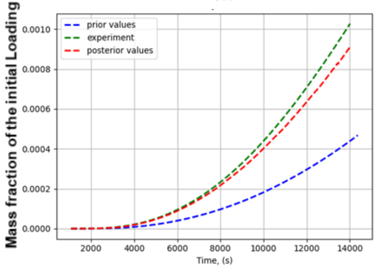


ASTEC+UQ



ASTEC+FSTC

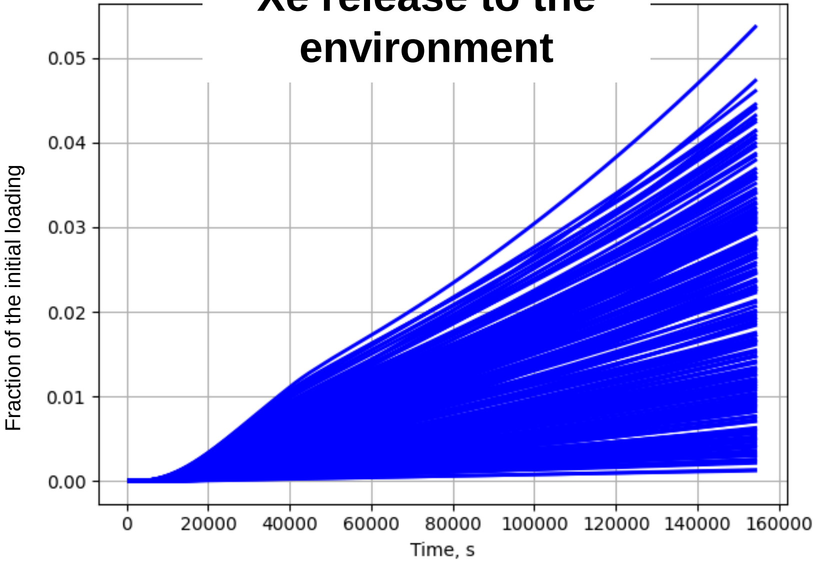


- **Assessing a database of source term results for:**
  - **Different scenarios**
  - **Different NPPs, i.e. KONVOI, VVER-1000, BWR Mark-I, SMR (on-going)**

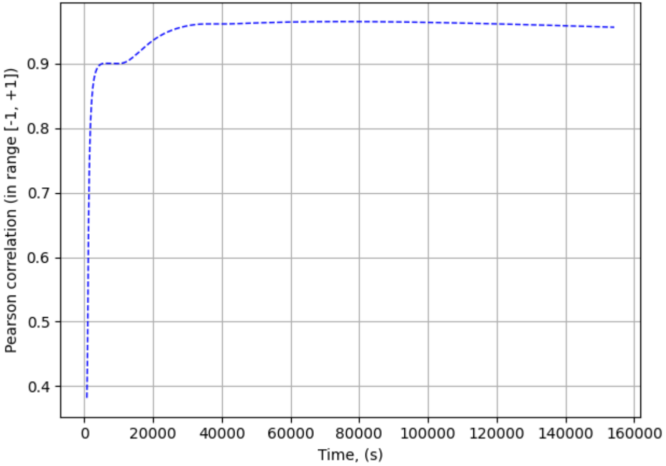
Source Term Database (UQ and Sensitivity)

- MBLOCA scenario in a generic KONVOI plant.
- 16 uncertain parameters, 300 ASTEC samples (2 failures), LHS employed

Xe release to the environment



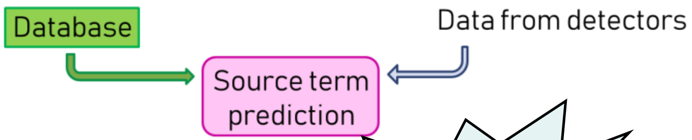
Xe release to the environment vs. Containment leakage



A. Stakhanova, et al., PRELIMINARY UNCERTAINTY AND SENSITIVITY ANALYSIS OF THE ASTEC SIMULATIONS RESULTS OF A MBLOCA SCENARIO AT A GENERIC KONVOI PLANT USING FSTC TOOL, Proc. of ERMSAR2022, 16-19 May 2022, Karlsruhe, Germany, DOI: 10.5445/IR/1000151444, https://publikationen.bibliothek.kit.edu/1000151444.

Source Term Prediction: Xe release to the Environment

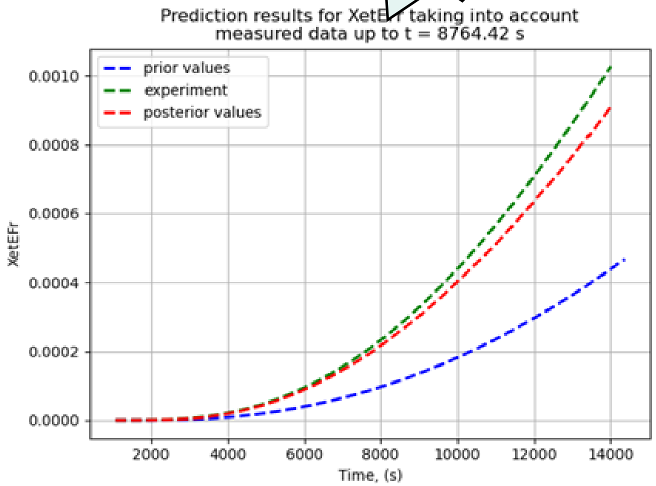
- Monte Carlo-based Bayesian inference model (MOCABA, Framatome) implemented in the FSTC tool



- **ASTEC+FSTC (KIT/Framatome collaboration work, BMWi WAME Project)**

First-of-its-kind

- Xe release predicted based on the total dose rate in the annulus
    - Results of 300 samples were used for ‘prior’
    - 100 samples employed as ‘experiment’
    - For both sets uncertainty of input parameters are the same
- **Good prediction results → Very promising approach**

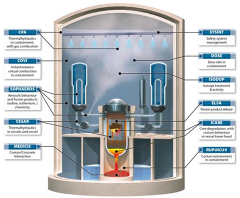


E. Pauli, A. Stakhanova, et al., Prediction of the Radiological Consequences of a Severe Accident Scenario in a Generic KONVOI Nuclear Power Plant, ERMSAR2022.

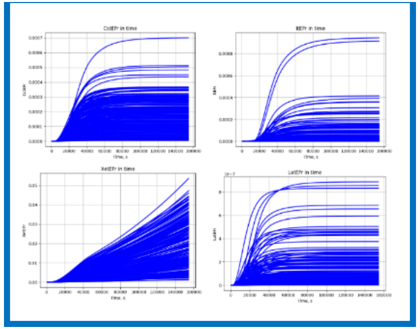
KIT calculation Platform (Extended route)

ST ± Sigma

Karlsruhe Institute of Technology

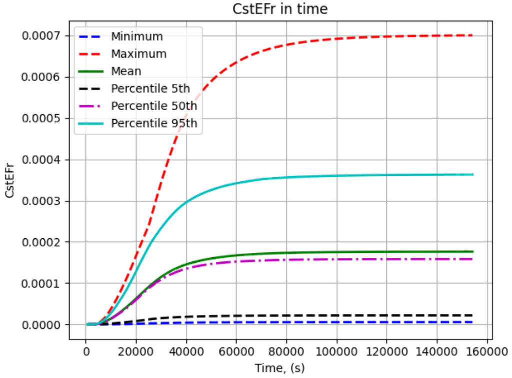


ASTEC/KATUSA
Source Term Database

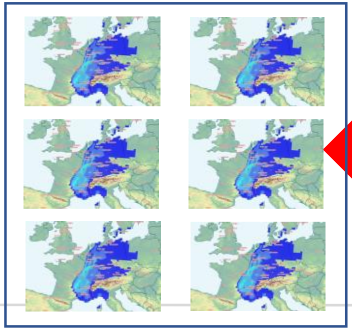


KATUSA

Uncertainty band of the FP release to the environment

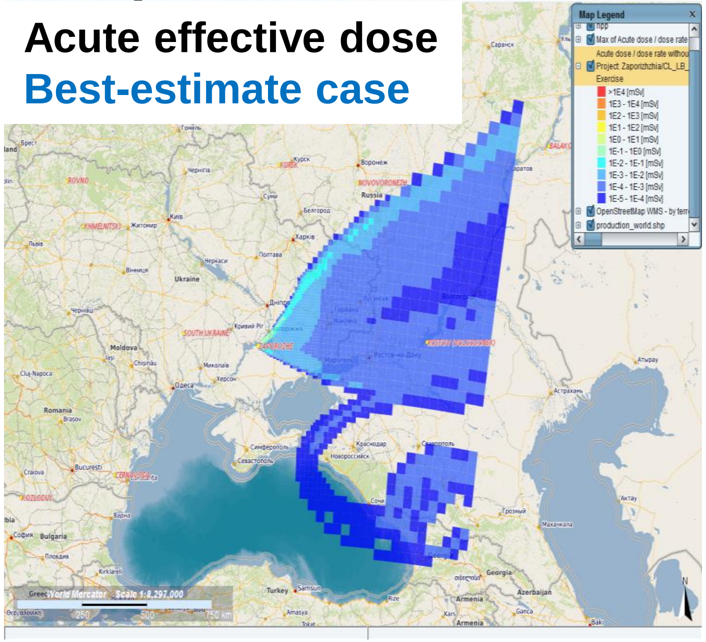


- **Providing JRODOS of the uncertainty band of the FPs release during a SA**
- **ASTEC/KATUSA/JRODOS data and platform already available**
- **GOAL: improvement in the definition of the Emergency Planning Zones**

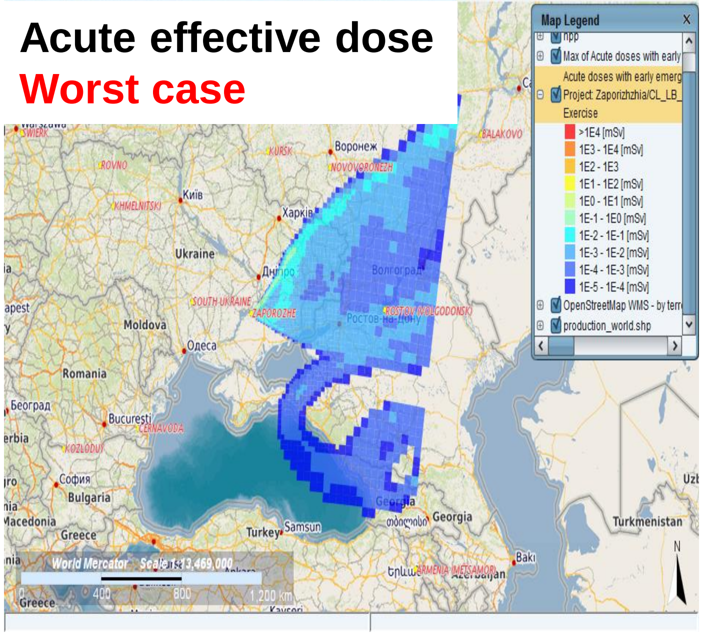


Effect of the ST Uncertainty on Radiological Consequences – Academic study (VVER-1000)

Acute effective dose
Best-estimate case



Acute effective dose
Worst case



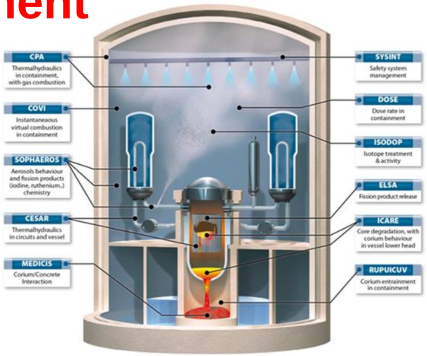
- Scenario SBO+MBLOCA on the cold leg scenario
- Site: Zaporizhzhia NPP
- **Maximum acute effective dose**: **Best-estimate = 16.7 mSv**, **Worst-case = 48.7 mSv**

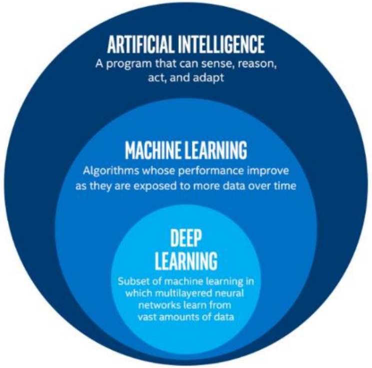
Housing New Approaches

- How to improve the current ASTEC/KATUSA/JRODOS platform?
- How to further improve the quality of the ST results to the emergency teams?
- How to house new technologies (for the SA research domain)?

AI/ML in SA Analyes: ‚Housing‘ new technologies

- **Artificial intelligence for the Simulation of Severe AccidentS (ASSAS) (2022-2026) (KIT as WP leader)**
  - Developing a proof-of-concept severe accident simulator based on ASTEC (Accident Source Term Evaluation Code).
  - Generation of training database for developing surrogate models to be implemented into ASTEC
  - **Joint INR/SCC contribution: KIT as unique and excellent multi-science environment**



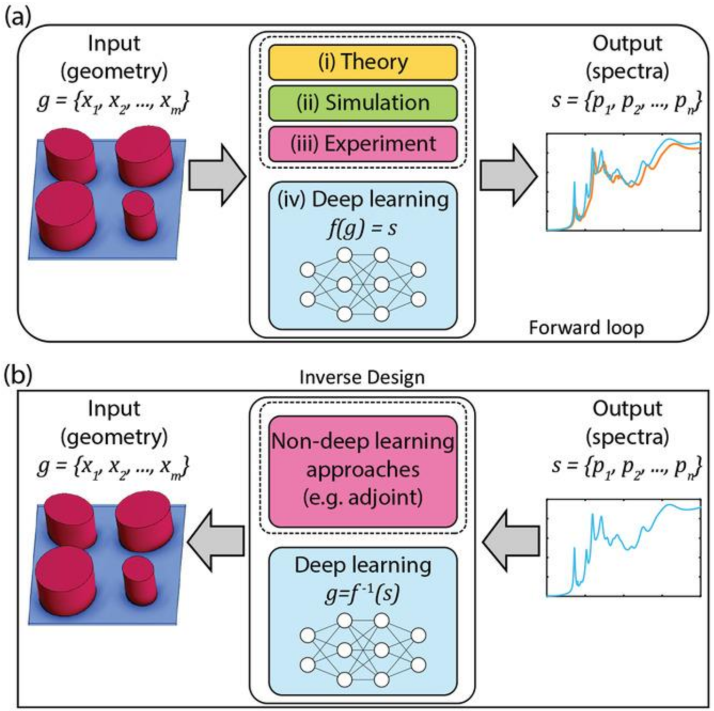


New Projects (AI/ML in SA Analyes)

- **Several potentialities to be explored**
  - Make the code much faster w/o loosing in accuracy

a. **Forward approach of the ASTEC+AI/ML**
  - Much larger database in the same wall-clock time → improvement ST prediction

b. **Backward approach of the ASTEC+AI/ML**
  - Forecasting when and which physical models might fail
  - Improvement of the code



Education, Training, and Dissemination

- Internships/student research projects, Master theses, Doctoral theses
- **Lectures** on reactor physics, reactor dynamics and safety analysis methods at the **Mechanical Engineering Faculty of KIT**
- Framatome Nuclear Professional School (see https://www.fps.kit.edu/)
- **KIT/CEA Frederic Joliot/ Otto Hahn Summer School** on Nuclear Reactors "Physics, Fuel, and Systems" (https://www.fjohss.eu/)
- 2023 FJ/OH: '*Digital Twins: New Horizons in Nuclear Reactor Design and Optimisation*', 23.08.2023-01.09.2023, GenoHotel, Karlsruhe
- Organization of 'The 10th European Review Meeting on Severe Accident Research' (**ERMSAR2022**), co-organized with IAEA and OECD/NEA (first time in ERMSAR)
    - 118 participants (50 organizations, 21 countries), 60 technical papers

ERMSAR Conference at KIT

22.06.2022: From May 16 to 19, 2022, scientists from 21 countries met in Karlsruhe at the 10th European Review Meeting on Severe Accidents Research (ERMSAR). The approximately 120 participants of the conference, which was hosted by KIT for the second time, presented and discussed current research results on severe accidents in nuclear power plants and possible preventive measures. One plenary session was specifically dedicated to the topic 'Fukushima: 10 (+1) years after'. For the first time, the IAEA and OECD/NEA were involved in the organization of the conference, in addition to the European research platforms NUGENIA and SNETP and their member institutions. On the last day of the conference, the participants visited the experimental facilities on severe accident research at KIT Campus North, which are embedded in the Programme Nuclear Waste Management, Safety and Radiation Research (NUSAFE).

https://www.nusafe.kit.edu/english/26.php

Conclusions

- Computational strategies are available and continuously under development at INR/RPD for
  - the **safety assessment of different reactor designs**
  - the **prediction of the radiological consequences from severe accidents**
- **The application cover any nuclear reactor plant**
- **Importance of the NUSAFE Program to preserve knowledge and capabilities**
- **Activities embedded in international co-operations with the US NRC and French IRSN**
- Active education, training, and dissemination work
- **Outlook (going on):**
  - **Small Modular Reactors (EU SASPAM-SA)**
  - **New rector components (ATFs) (OECD/NEA QUENCH-ATF, IAEA CRP ATF-TS)**
  - **Innovative calculation 'routes' employing AI/ML algorithms (EU ASSAS)**