Karlsruhe Institute of Technology

KIT Computational Route for the Safety Assessment and Radiological Risk Prediction of NPPs

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Presented by L. Mercatali

Institute for Neutron Physics and Reactor Technology (INR)

Outline

- Motivation
- Challenges for the Computational Tools for Safety & Risk Assessment
- KIT Computational Route for Safety Assessment of NPPs
  - Multiphysiscs
  - Multi-scale
- KIT Computational Route for Estimation of radiological risk from NPPs
- Final remarks

Motivation

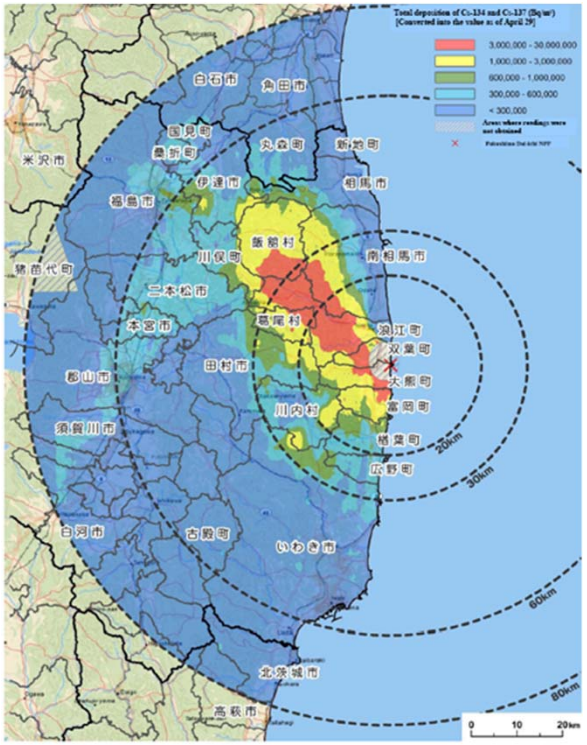
- Nuclear energy use for electricity generation ends April 2023
- Dismantling of Nuclear Power Plants will last for decades
  - Expertise in nuclear power plants, reactor physics, radiation protection, etc.
- Many NPP under operation around Germany and worldwide
  - VVER-1200, AP-1000, EPR, LW-SMR, APR1400, research reactors, etc.
- Hypothetical severe accidents with FP-release cannot be excluded
  - National regulators: want to know reliable data about expected radiological risk (amount and timing of FP-releases around the NPP)
- Germany: Keep expertise on Methodologies to assess the **hypothetical risk** that may arise from the operation of NPPs
  - One of the HGF mission

Potential Risk
from NPPs under operation around Germany

2023
April

Number of NPP around Germany:
5+58+7+15+1+10+6= 102

Radiological consequences of hypothetical Severe Accidents AROUND GERMANY



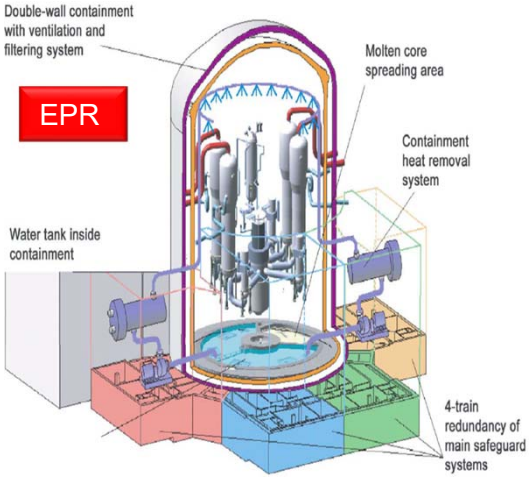
Fukushima: Cesium 137 Contamination (measured)

Challenges for the Computational Tools for Safety & Risk Assessment

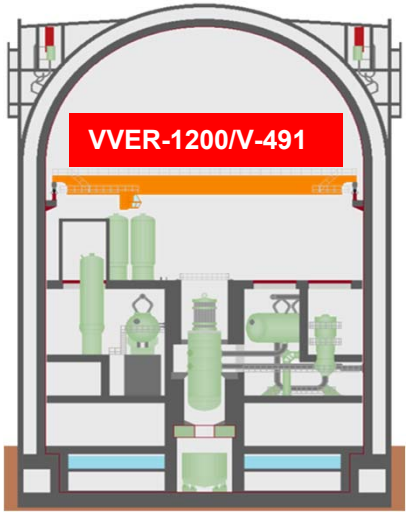
Drivers
for the continuos development of numerical tools

- Continuous development of nuclear power plant technology
- Improve economics, operational flexibility and safety standards
- Advances in numerical algorithms and computer power
  - Availability of huge and cheap HPC-clusters
  - Pave the way to increase prediction accuracy, fidelity and spatial discretization of computational domains

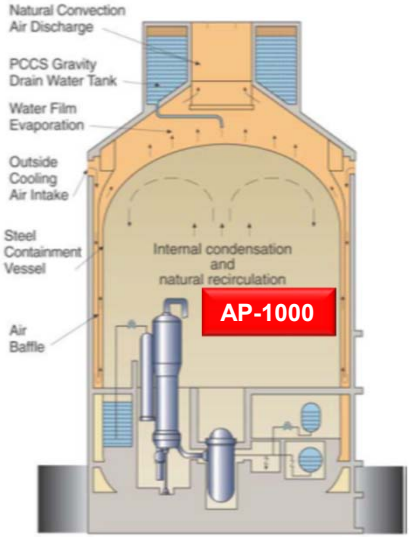
NPP Technology Developments: Drivers



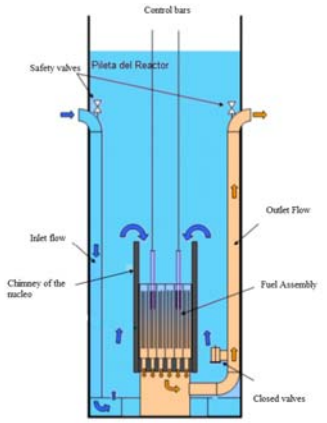
EPR



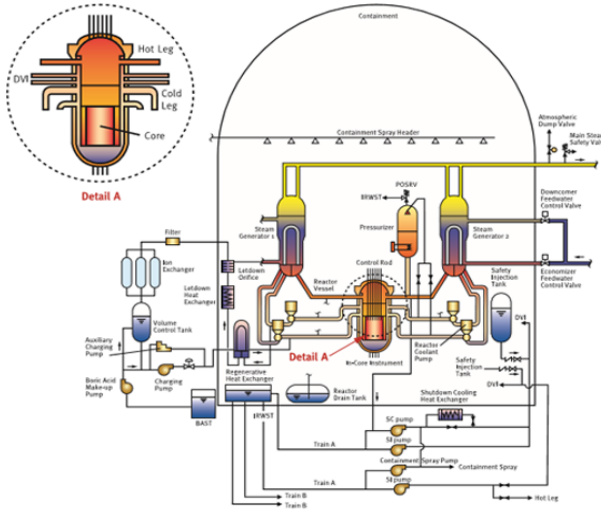
VVER-1200/V-491



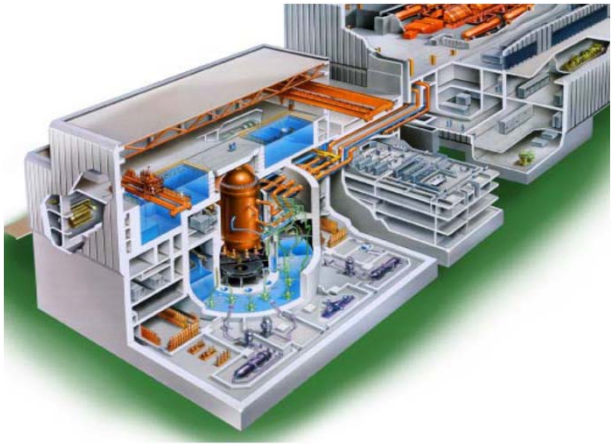
AP-1000



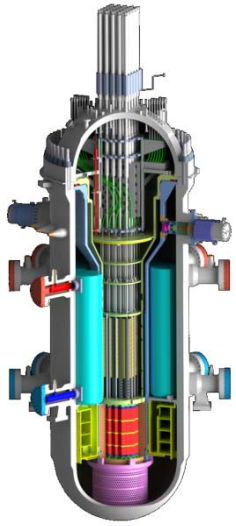
RR with MTR-Fuel



APR1400



GE ABWR

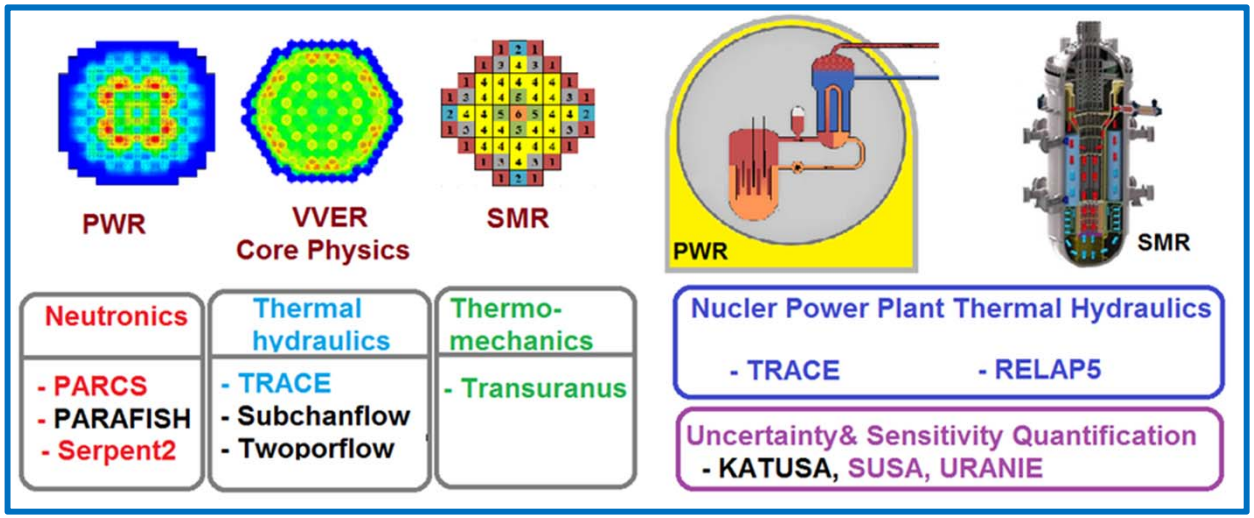


SMR SMART

KIT Computational Route for Safety Assessment of NPPs

KIT Computational Route for NPP Analysis

- **KIT computational tools for the analysis of Design Basis Accidents (DBA)**



In-house codes:
- PARAFISH
- TWOPORFLOW
- SUBCHANFLOW
- KATUSA

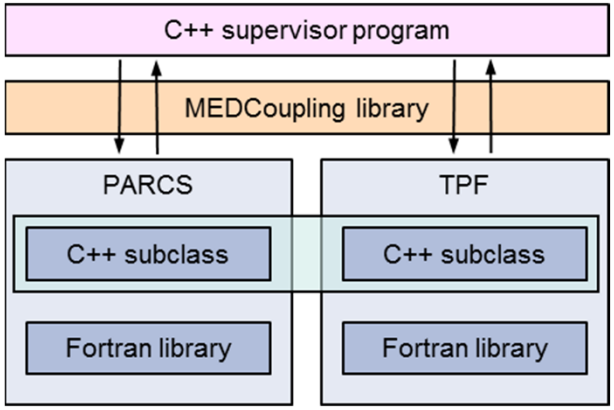
- **KIT Strategy:**
  - **Development of in-house codes (Parafish, SCF, TPF, KATSA)**
  - **Use of international codes embedded in international co-operations (USNRC CAMP)**
  - **Extend capability of international codes: multiphysics and multi-scale coupling**
  - **Validation using data from in-house tests (COSMOS-L /-H) and external data**

KIT: Multi-physics Approach for Core Analysis

- Improved core thermal hydraulics (in-house):
  - Subchannel codes: SUBCHANFLOW (SCF)
  - Porous-media two-phase flow 3D code: TWOPORFLOW (TPF)
- Improved neutronics:
  - Parallel finite element neutronic transport solvers e.g. PARAFISH (in-house)
  - Monte Carlo codes: MCNP, Serpent2 (external)
- Uncertainty & sensitivity analysis tools
  - KATUSA (**KA**rlsruhe **T**ool for **U**ncertainty and **S**ensitivity **A**nalysis)
- Coupling of in-house codes (TH, N) with external nodal Diffusion and Monte Carlo solvers: Flexible and modular approach (ICoCo)
  - SUBCHANFLOW/PARCS, TWOPORFLOW/PARCS
  - PARAFISH/TWOPORFLOW
  - SUBCHANFLOW/Serpent2 (novel transient analysis based on MC)

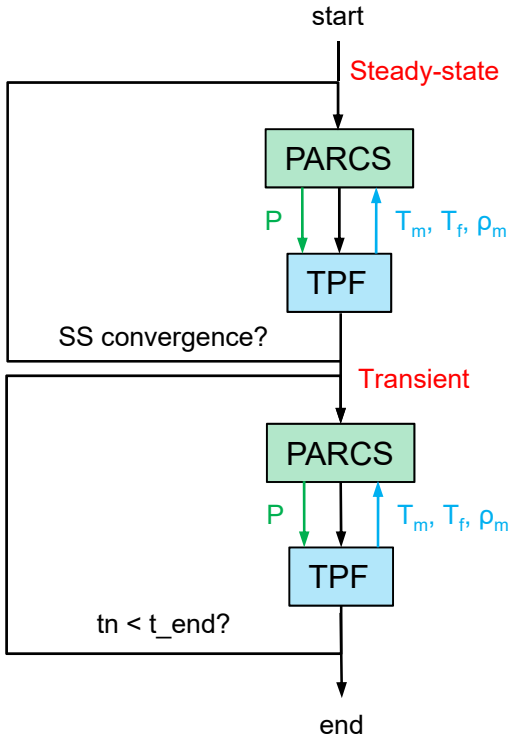
KIT approach:
Multiphysics coupling based on ICoCo

- Multi-physics core analysis



ICoCo-Based Coupling

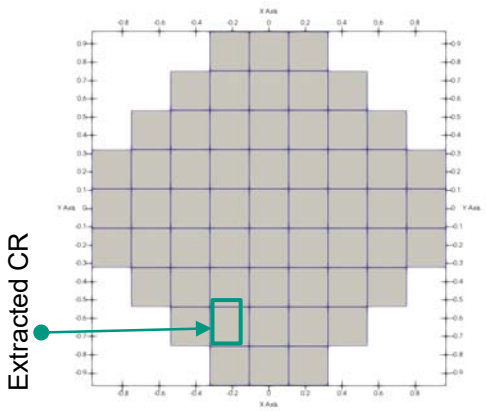
- **Key features:**
  - Flexible and modular
  - Domain overlapping: mesh to mesh superposition (N ←→ TH)
  - Automatic exchange of “Feedback parameters”: MEDCoupling library
  - Inbuild interpolation methods (1D, 2D, 3D)



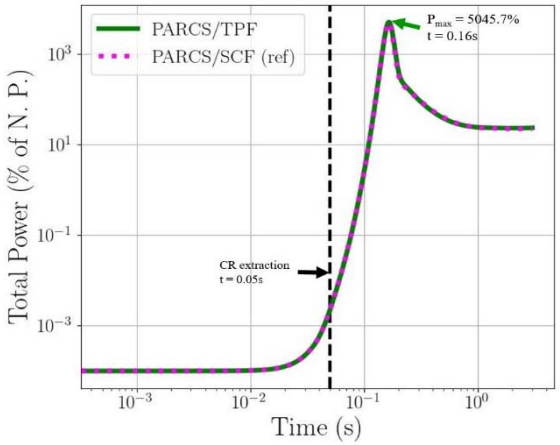
Flowchart of PARCS/TPF Coupling (Explicit OS Picard Iteration)

KSMR: REA Analysis at HZP

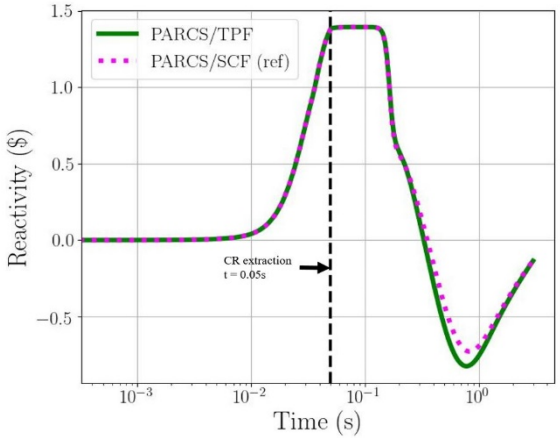
- REA at Hot zero power (HZP)
- CR worth of extracxted rod: 0.725 $



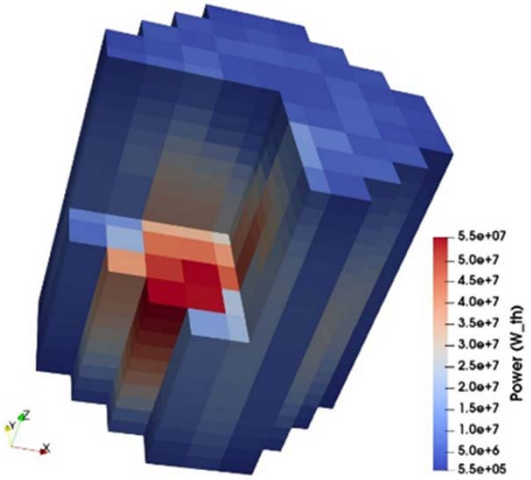
Parameter	Value
Initial core power	1.0E-4 %
Highest CR worth	1.45 $
Ejection duration	0.05 s
End of transient simulation	1.0 s



KSMR: Evolution of the total power after REA



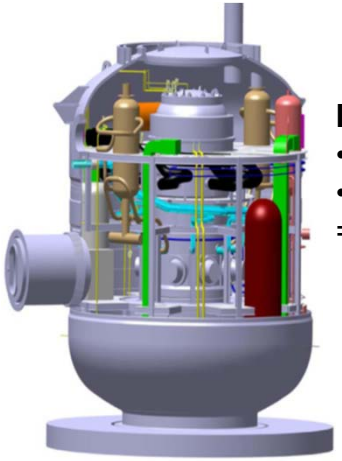
KSMR: Evolution of the total reactivity after the REA



3D Core radial power distribution

Multi-physics /-scale Plant Analysis Methodologies

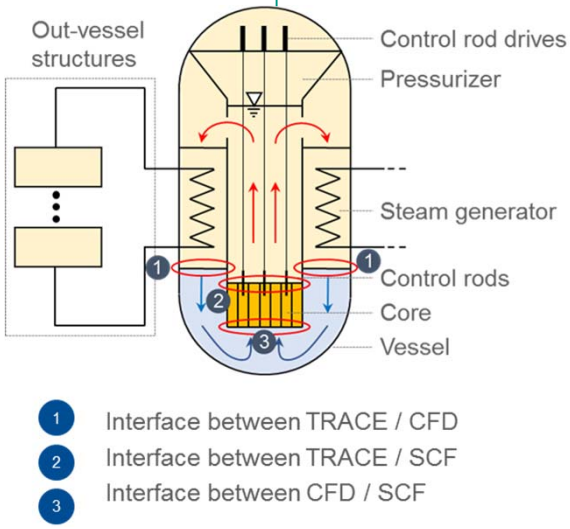
Methods for Safety Evaluations of NPPs



Integrated RPV
- Pumps
- HXs

=>3D flow

French NUWARD Design

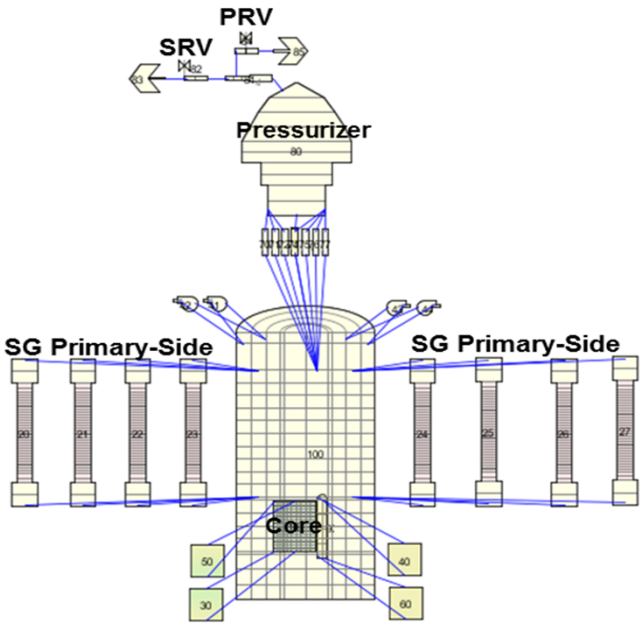


ICoCo-Based Coupling

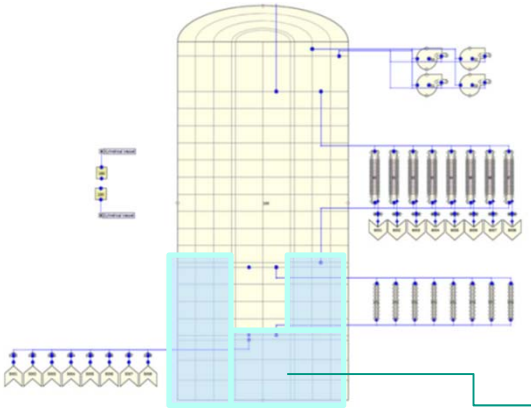
McSAFER Solution Approach:

- Industrial tools:
  - 1D / 3D coarse mesh TH codes: TRACE, RELAP5, etc.
- KIT research tools:
  - Multiscale coupling of system TH with subchannel-codes
    - TRACE/SCF/PARCS
  - Multiscale coupling of system TH with CFD-codes
    - TRACE/OpenFOAM/PARCS

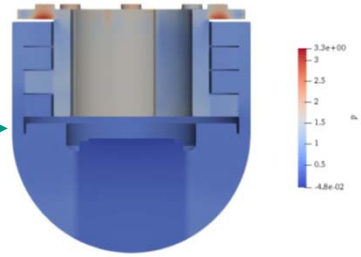
KIT Analysis Approach: TRACE/PARCS/OpenFOAM



TRACE Domain: Core + RPV + Plant



TRACE Domain: Core + RPV



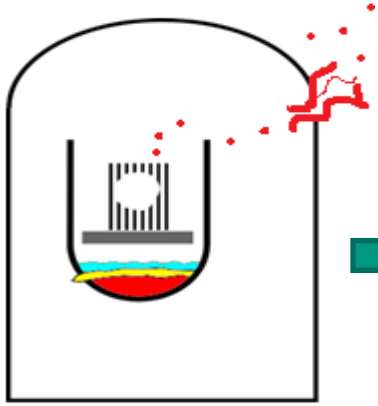
OpenFOAM Domain

ICoCo-based TRACE-OpenFOAM and PARCS/TRACE coupling

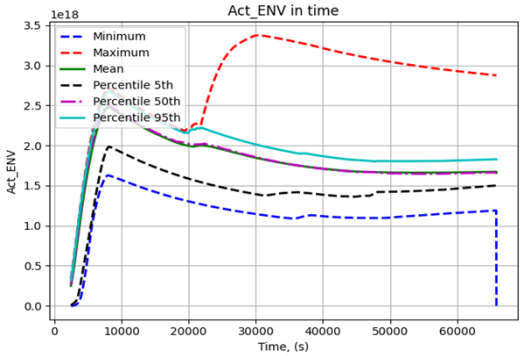
KIT Computational Route for Estimation of radiological risk from NPPs

Prediction
of the radiological risk of Severe Accidents

- **Emergency TEAM main concern:** Time and amount of FP-release to the ENV!

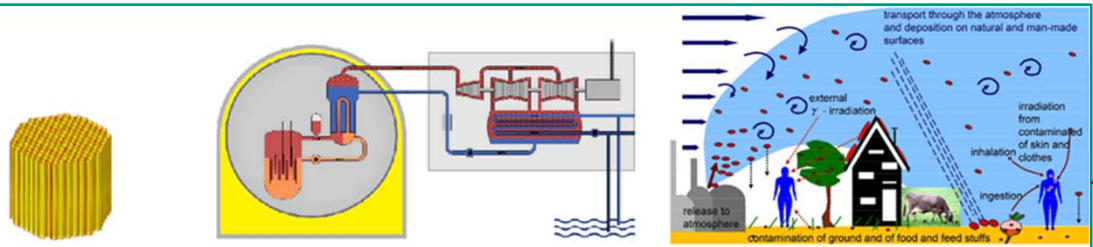


PWR severe accident



ASTEC: Time and amount of Activation including uncertainty band

- **Required computational tools needed for reliable prediction of the radiological impact: Neutronic, system thermal hydraulic, severe accident codes, and radiological impact (dispersion of FP)**



Core Physics: depletion, nuclide inventory
- KORIGEN
- ORIGEN-S

Severe Accident Phenomena: In-vessel, RPV-failure, ex-vessel, Containment
- Integreal code ASTEC
- Integral code MELCOR

Radiological Risk around a NPP due to radionuclide dispersion in the environment
- JRODOS

KIT Strategy for Severe Accident Research

- **Strategic partnership with leading EU (France: IRSN) and international (US NRC) organizations**

RODOS / JRODOS

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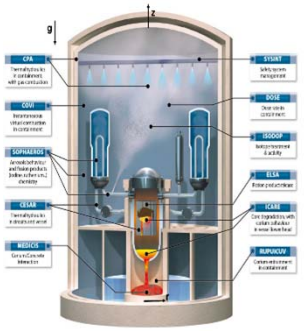
ASTEC

European Severe Accident Code (IRSN)

ASTEC User Group: 40 organizations:
- **EU**
- **Asia: China, India, Korea**
- **East Europe: Russia, Lithuania, Belarus, Bulgaria, Romania, Hungary**
- **America: Canada**

ASCOM User Group Community



Validation

- **KIT Experimental facilities e.g. MOCKA, BETA, LIVE, CORA, QUENCH**
- **External data: PHEBUS, etc.**

MELCOR

Cooperative Severe Accident Research Program (CSARP)
MELCOR Code Assessment Program (MCAP)
- Many partners from EU, Asia, East Europe, etc.

EMUG User Group Community

- **Internationalization and knowledge gain due to regular meetings around the world**

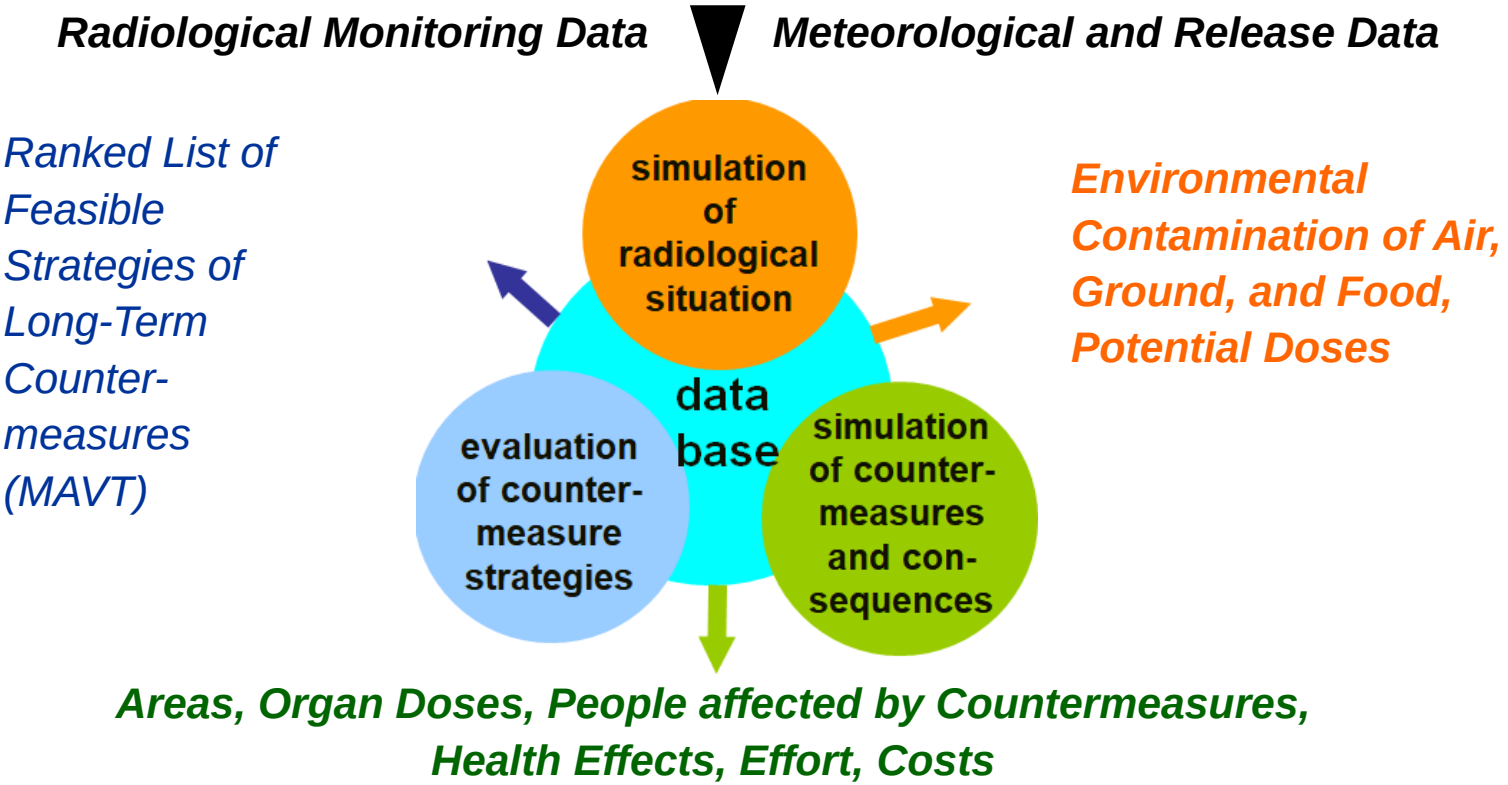
RODOS/JRODOS

decision support system for off-site nuclear emergency management

- Provide consistent and comprehensive information at local, regional and national levels, for all accident phases
  - During real event (housing and displaying of relevant information about the release, the weather, the contamination; forecast of health, agricultural and economic impacts with and without the application of countermeasure)
  - When preparing for a possible future event (creating scenarios and background material for planning, exercises and training)
- Assist decision makers in evaluating different measures against a range of quantitative and qualitative criteria
- Promote a common emergency management frame aiming to move away from national solutions

RODOS/JRODOS:
Real-time On-line Decision Support system

- JRODOS tasks, input data, output



RODOS/JRODOS: EMERGENCY chain models

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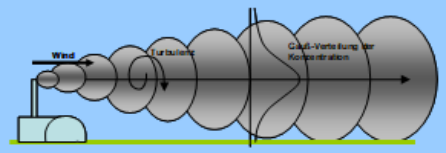
Released activity (Measurement / User)

Meteorological data (Measured / Prognostic / User)

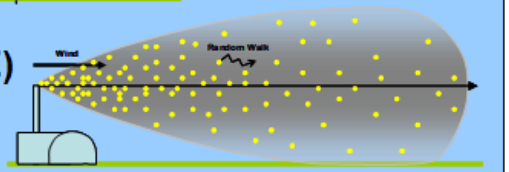
Further data (from JRodos Data bases)

LSMC: Atmospheric dispersion and deposition, local scale (up to several 100 km)

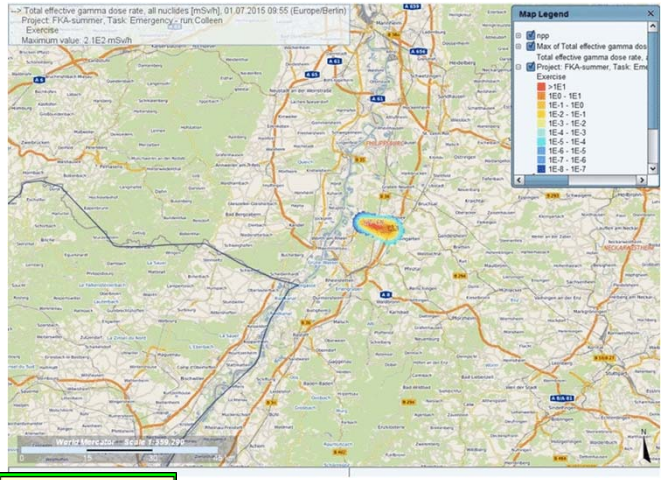


Rimpuff (DEN)
Atstep (IKET)

Dipcot (GRE)
Lasat (GER)

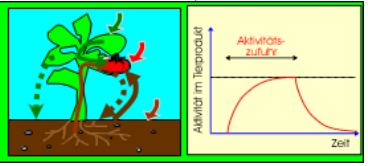


Accident
Release of
52 hours



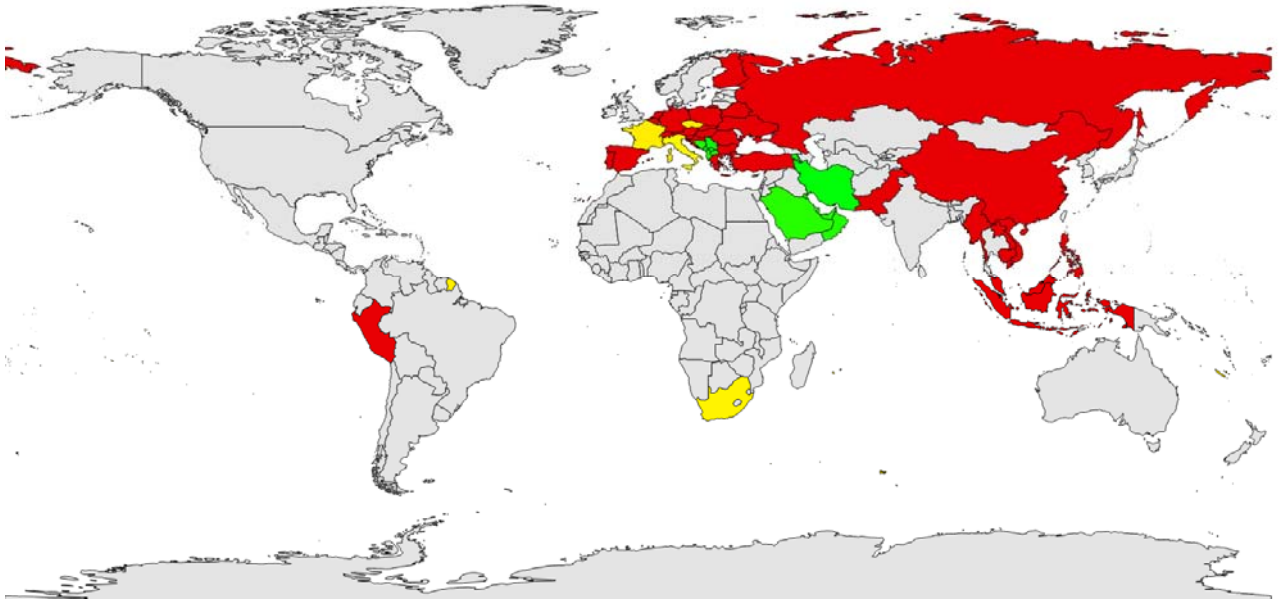
Dose rate and dose, early countermeasures

Food chain and dose model, terrestrial FDMT (GER)



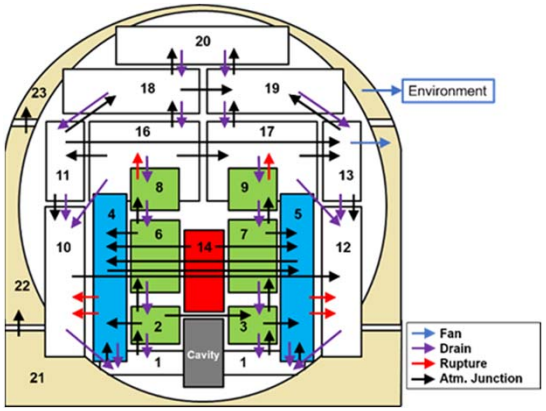
RODOS/JRODOS:
Real-time On-line Decision Support system

- World-wise installations (>40 countries, ongoing)

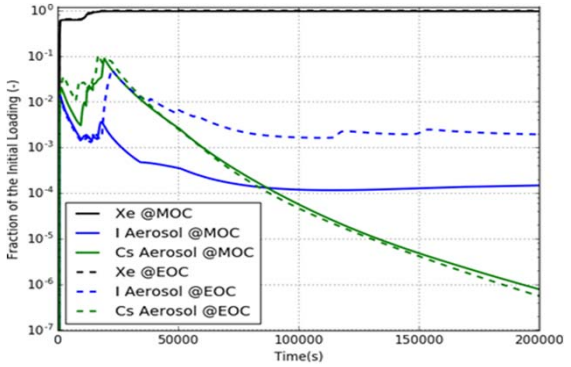


- RODOS installation
- RODOS local users
- Ongoing Installations in West Balkan countries, GCC countries and Iran

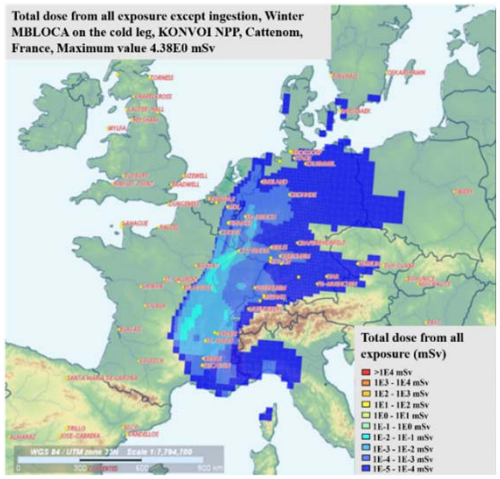
Examples:
PWR Konvoi Radiological Consequences



ASTEC: KONVOI PWR containment model



ASTEC: Amount of Xe and I and Cs aerosols in containment as fraction of the initial fuel mass in the core in the MBLOCA



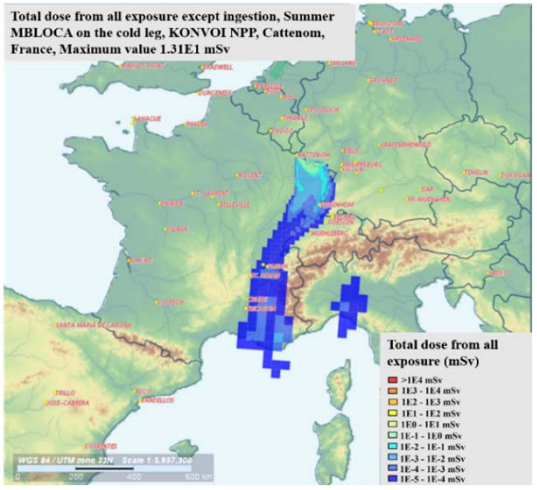
JRODOS: Total dose from all exposure 10 days after a hypothetical MBLOCA accident in a generic KONVOI NPP at the Cattenom site: Winter time.

Computational tools:

KORIGEN

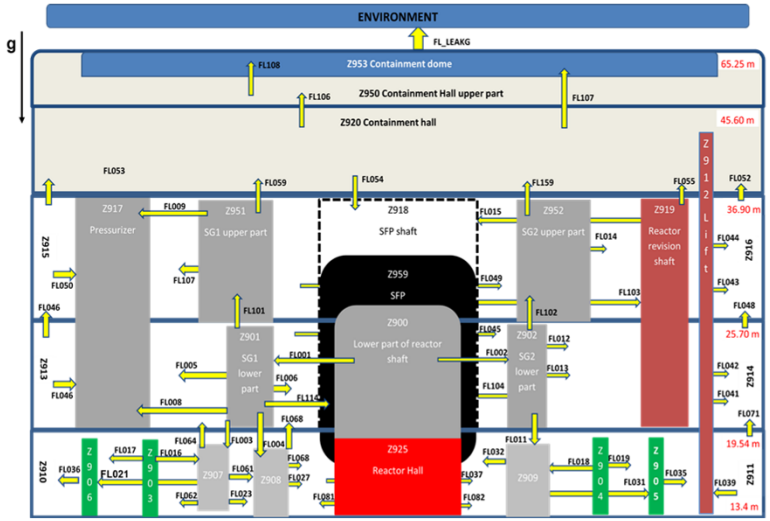
ASTEC

JRODOS

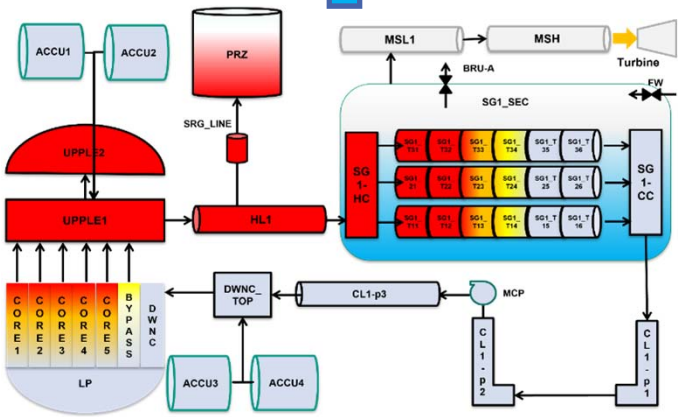


JRODOS: Total dose from all exposure 10 days after a hypothetical MBLOCA accident in a generic KONVOI NPP at the Cattenom site: Summer time.

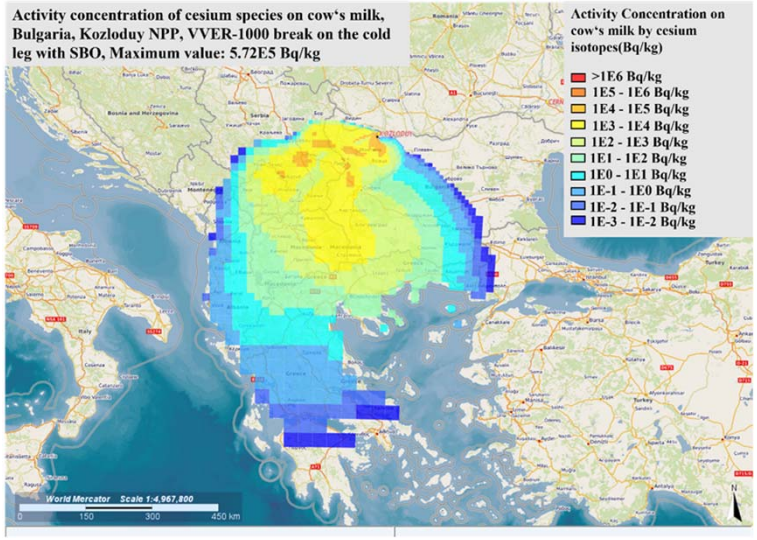
Examples:
VVER-1000 Radiological Consequences



ASTEC: VVER-1000 Containment Model



ASTEC: VVER-1000 Primary and Secondary Plant Model



JRODOS: Simulated maximum activity of cesium isotopes in the cow's milk at the end of 10th day of radiological dispersion for the LBLOCA on the cold leg accident case with Station Black Out

Computational tools:

KORIGEN + ASTEC + JRODOS

Final Remarks

- **KIT computation route** established at KIT thanks to the Helmholtz NUSAFE long- term research program (KIT, HZDR, FZJ)
  - Allow safety assessment of different reactor designs and
  - Make possible the prediction of the radiological risk from severe accidents that may happen elsewhere in the world
- KIT research activities are embedded in international co-operations with the US NRC and French IRSN
  - National: HZDR, FZJ, GRS, RUB, UNI STU, FRAMATOME, WED, PEL, etc.
  - International: VTT, CEA,UPM,, PSI, KTH, TRACTBEL, ENEA, CIEMAT, etc.
  - Active contribution to OECD/NEA, IAEA research projects
- **Computation route** for safety and risk analysis is supported by KIT experimental research program (e.g. QUENCH, COSMOS facilities)
- **Expertise** on reactor physics and neutronics are highly relevant for safety investigations of intermediate waste storage (inventories, decay heat) and for the optimization of the decommissioning of NPPs

Back-up slides

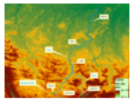
RODOS/JRODOS:
Key features of Real-time On-line Decision Support system

- Multi-user operation in national/regional emergency centres for off-site nuclear emergency management
- Provision of information for decision-making
  - on local / national / regional / European scales,
  - in the early and later phases of an accident,
  - for all relevant emergency actions and countermeasures.
- Wide IT applicability - HP-UX and Linux (RODOS), Microsoft Windows and Linux (JRODOS)

JRODOS:
Hydrological models in (SSK group)

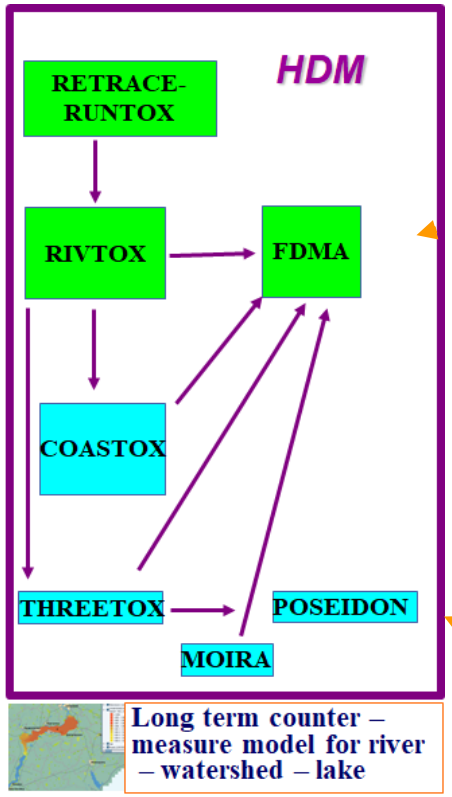
Radionuclide wash-off from watersheds

(1-D) river flow, sediments and radionuclide transport models



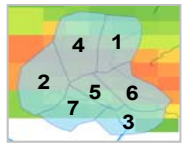
(2-D) reservoirs, floodplains and coastal areas model

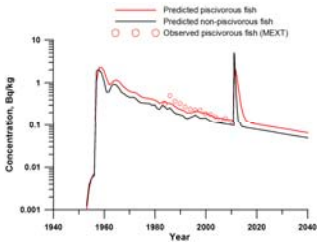
(3-D) deep river reservoirs, lakes and marine environment



Long term counter – measure model for river – watershed – lake

Freshwater food chain and dose model





Marine food chain and dose model