



FISA 2019

9th European Commission Conference
on EURATOM Research and Training
in Safety of Reactor Systems

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Pitesti, Romania



ADVANCED NUMERICAL SIMULATION AND MODELLING FOR REACTOR SAFETY – CONTRIBUTIONS FROM THE CORTEX, HPMC, MCSAFE AND NURESAFE PROJECTS

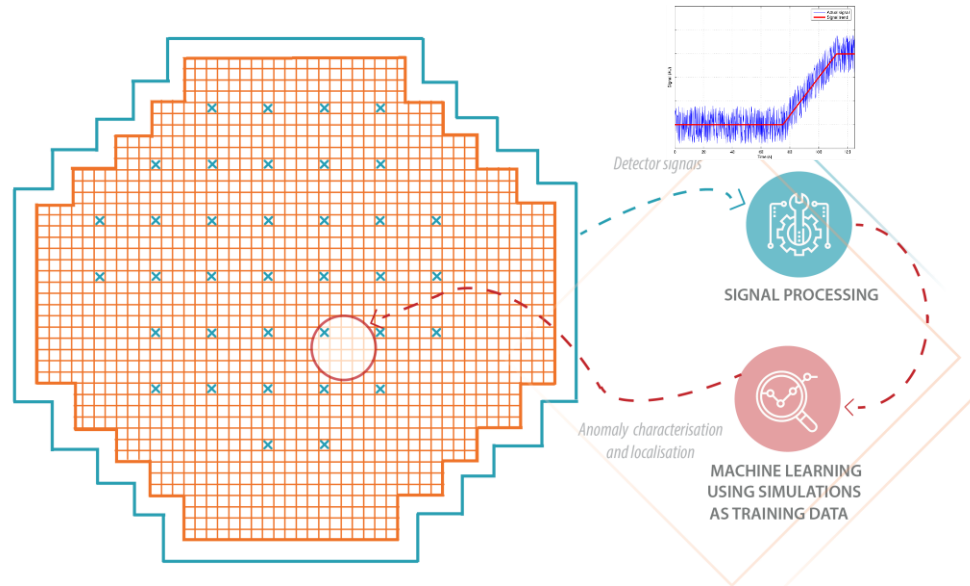
C. Demazière (Chalmers University of Technology, Sweden)
V. H. Sanchez-Espinoza (Karlsruhe Institute of Technology, Germany)
B. Chanaron (Commissariat à l’Energie et aux Energies Alternatives, France)

Introduction

- **Predictive simulations** = backbone of nuclear reactor safety
- Most of the tools developed when **computing** resources and capabilities were **limited**
- Shift towards **high-fidelity methods** taking advantage of progress in computing (hardware/software)
- Reactor **operating closer to their safety limits** due to less conservative safety evaluations
- Importance of **core monitoring** (+ operational problems more frequent due to ageing fleet)
- Presentation of four projects funded by the European Commission on **advanced numerical simulation and modelling for reactor safety**

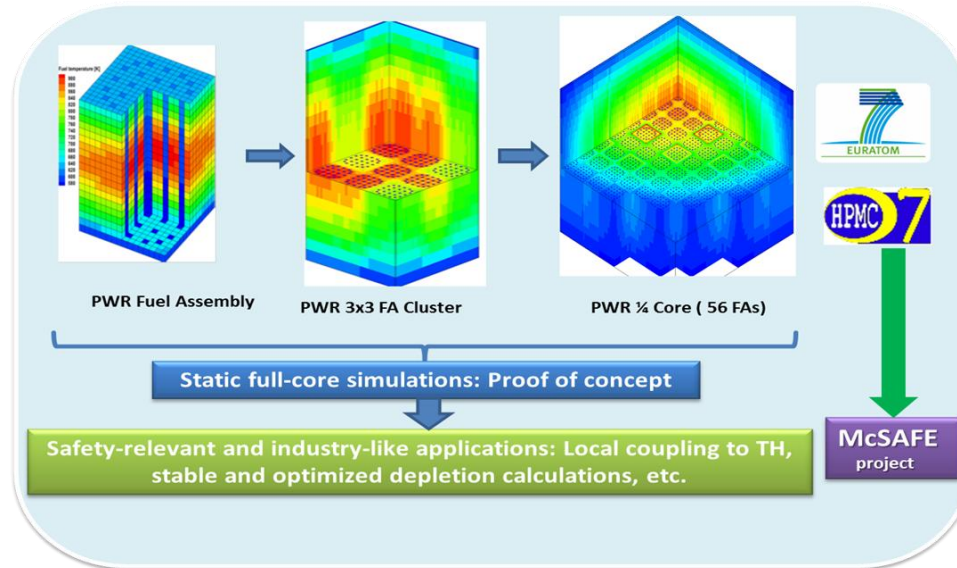
Short description of the respective projects

- **CORTEX**: CORe monitoring Techniques and EXperimental validation and demonstration
 - Aim: develop a core monitoring technique for the early detection, localization and characterization of anomalies using **neutron noise**



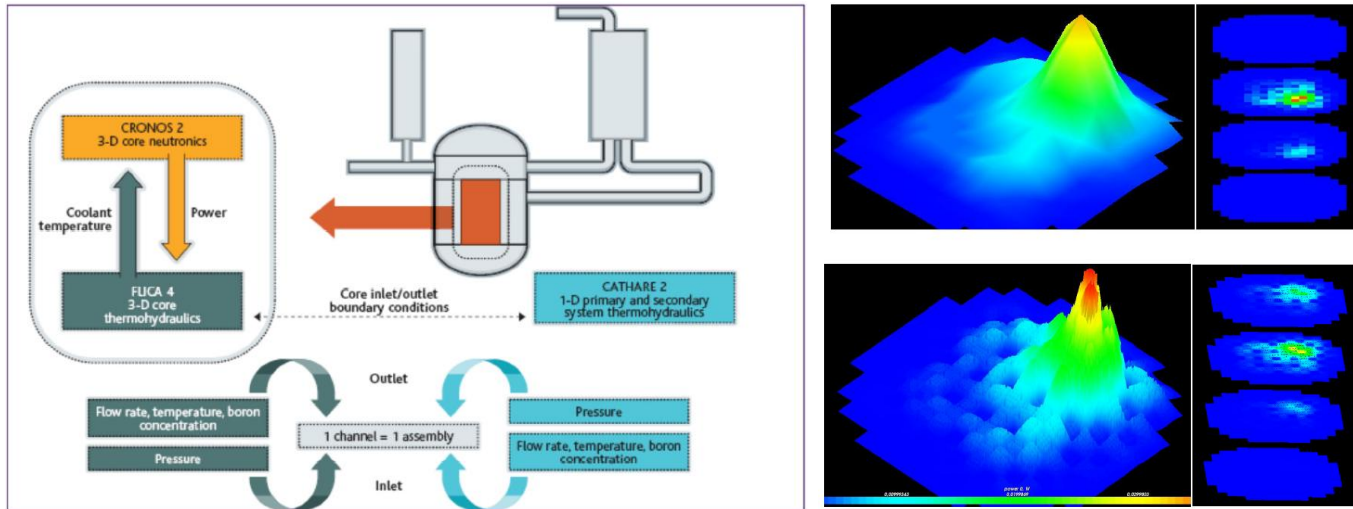
Short description of the respective projects

- **HPMC**: High Performance Monte Carlo Methods for Core Analysis
- **McSAFE**: High Performance Monte Carlo Methods for SAFETY Analysis
- Aim: develop high fidelity multi-physics simulation tools based on Monte-Carlo techniques for neutron transport



Short description of the respective projects

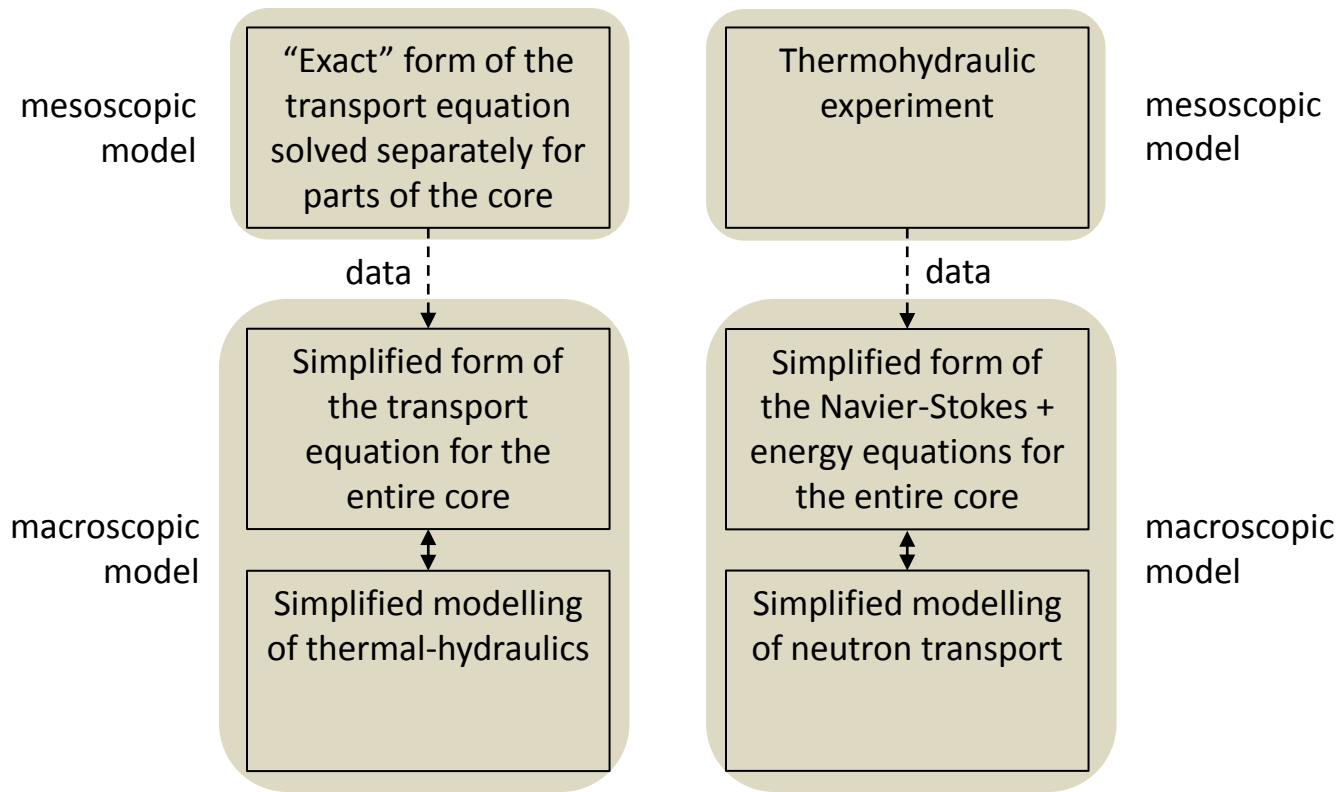
- **NURESAFE:** NUclear REactor SAFETY simulation platform
 - Aim: develop a European reference tool for higher fidelity simulation of LWR cores for design and safety assessment



Dynamic 3D coupling of codes : core physics, thermohydraulics, fuel thermomechanics.
Release of industry-like applications. Uncertainty quantification

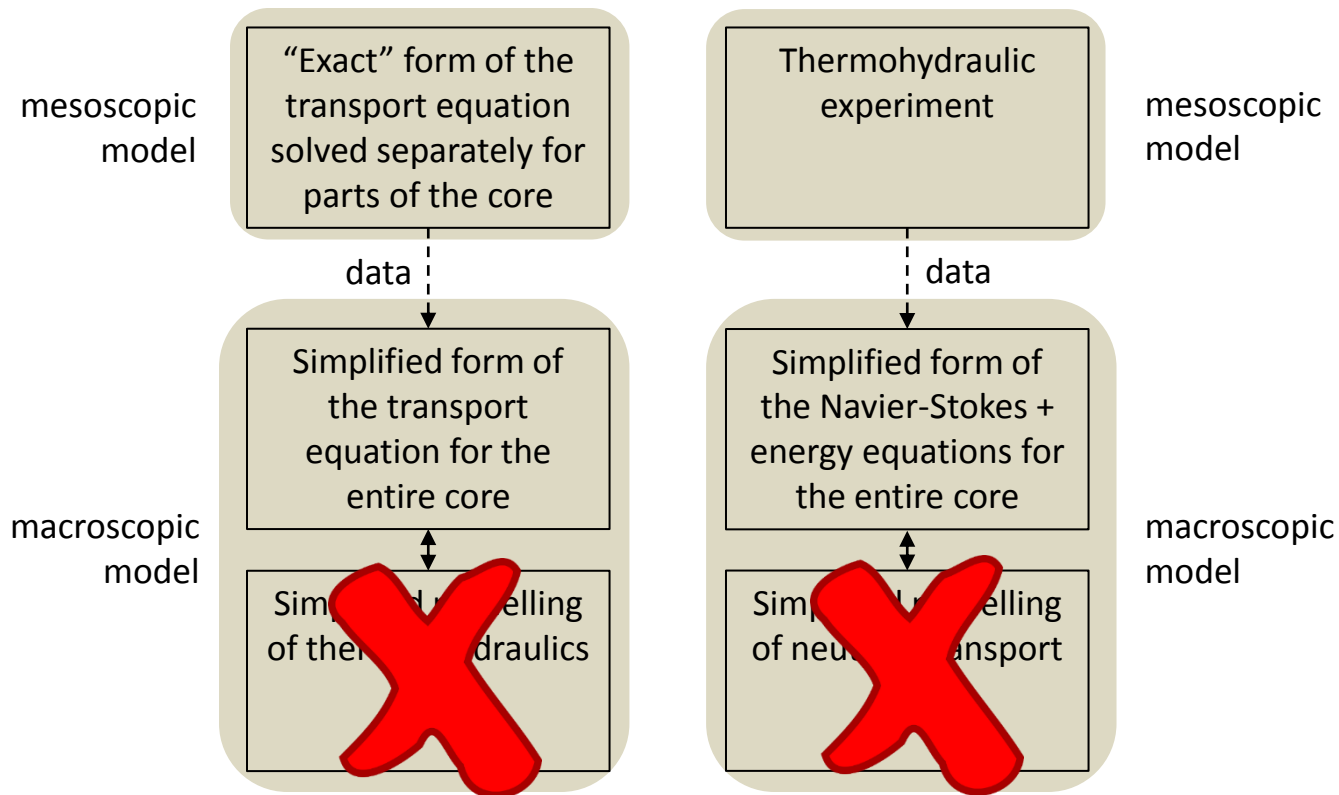
Key objectives and achievements for advanced numerical simulation and modelling

- From “divide-and-conquer” ...



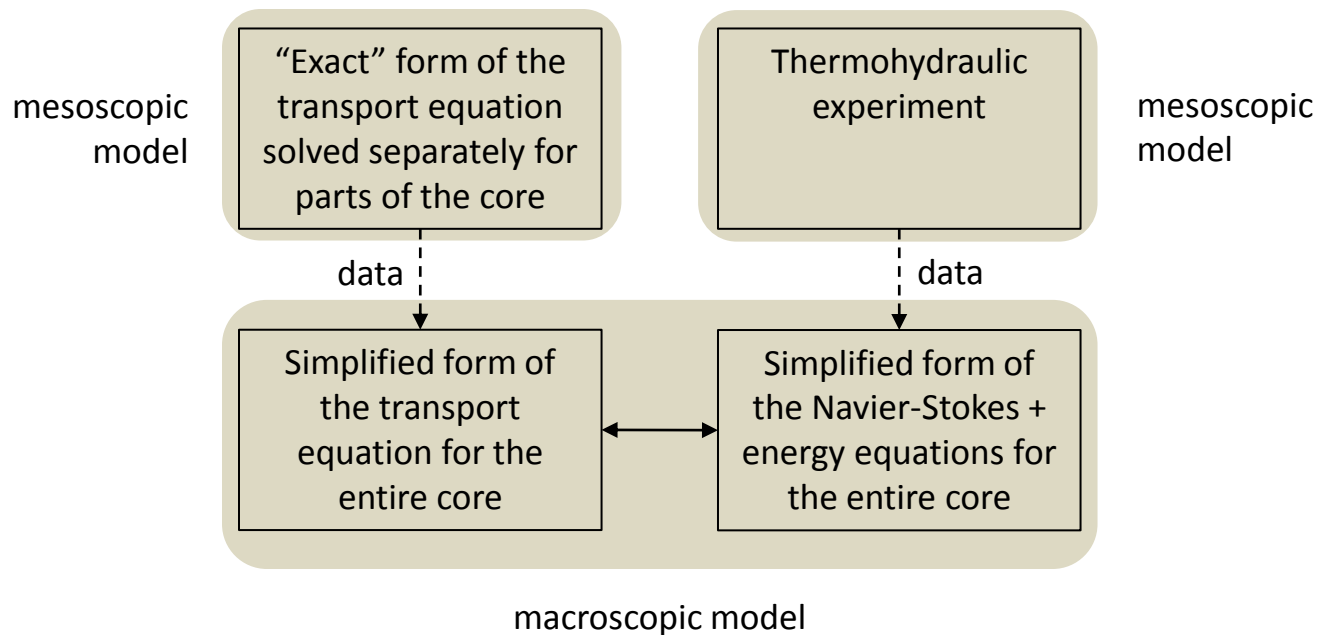
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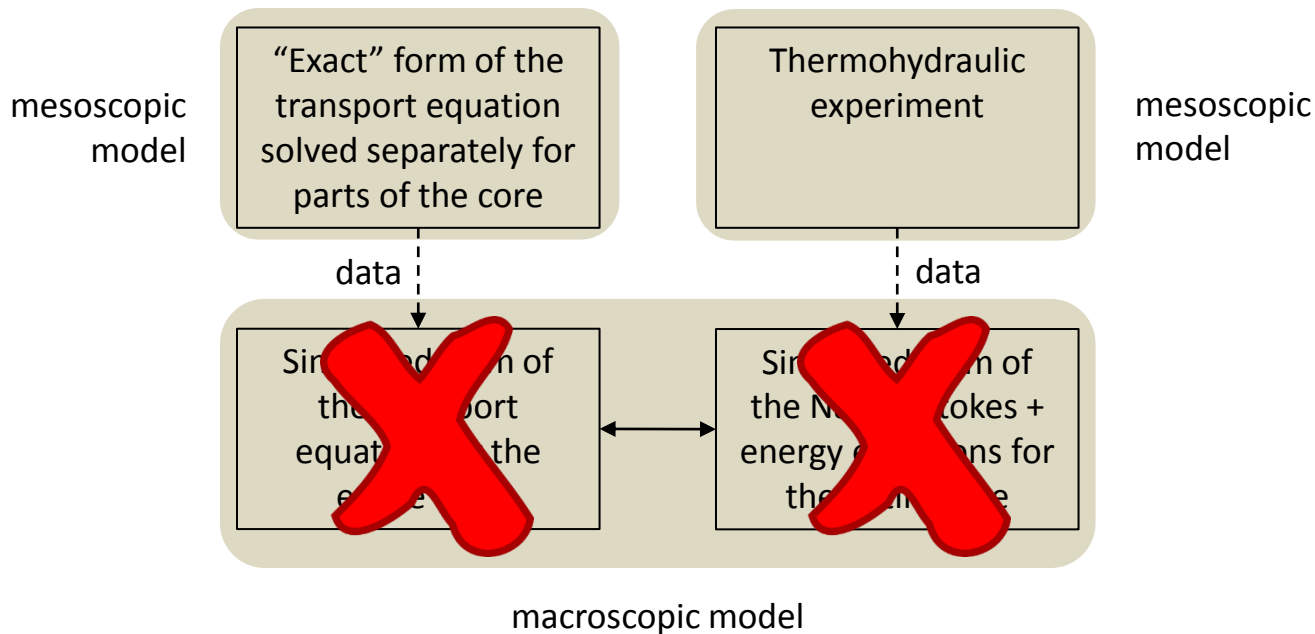
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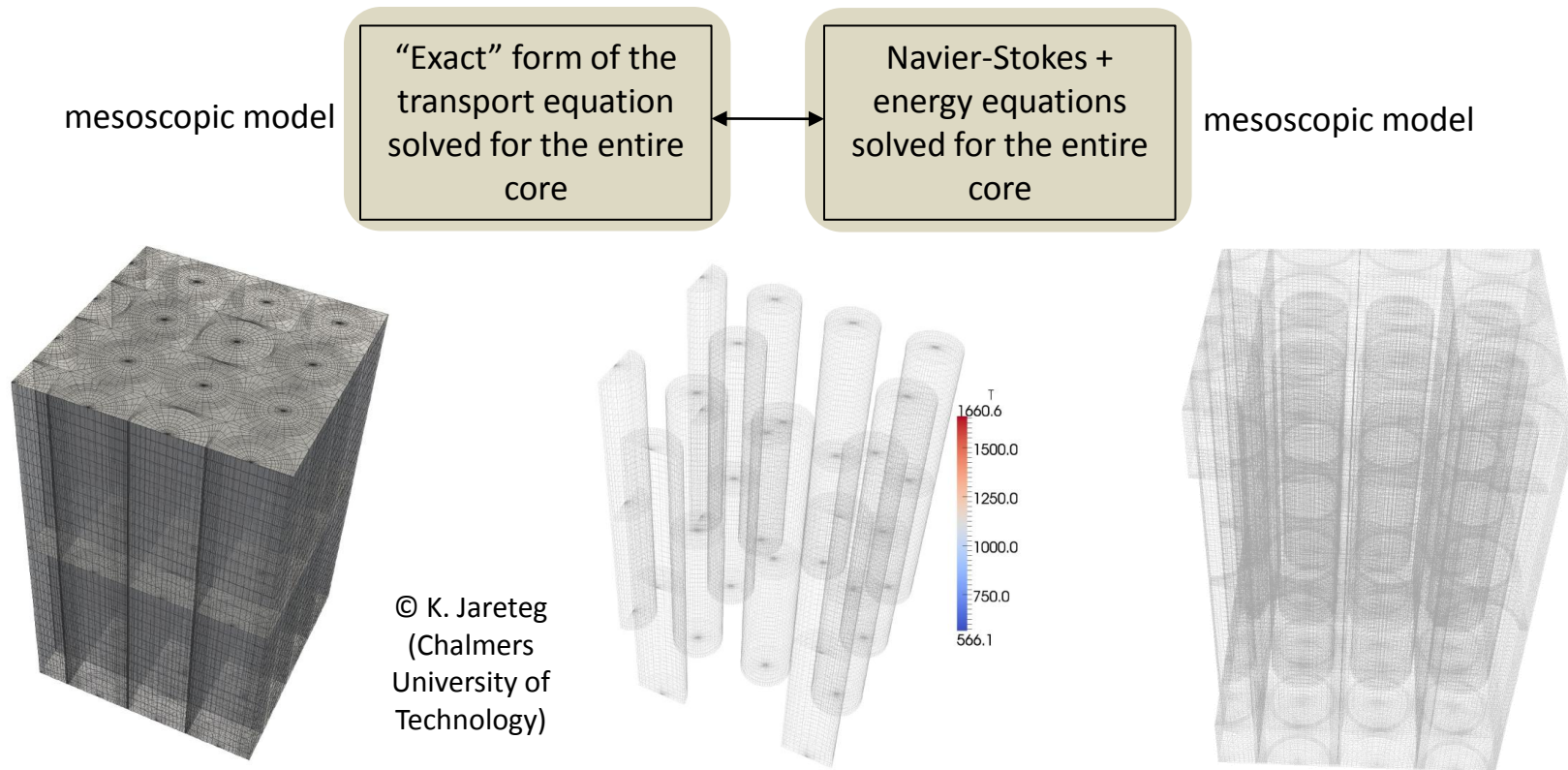
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Key objectives and achievements for advanced numerical simulation and modelling

- From “divide-and-conquer” to integrated models



- **CORTEX:**

- Development of modelling capabilities for estimating the transfer function

Several complementary approaches:

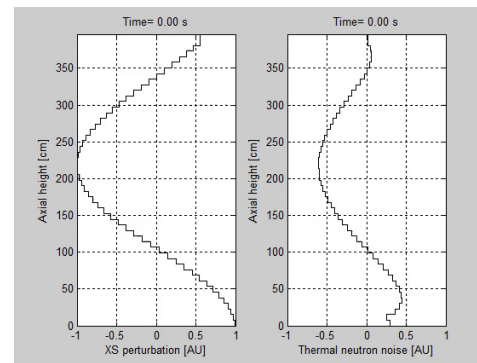
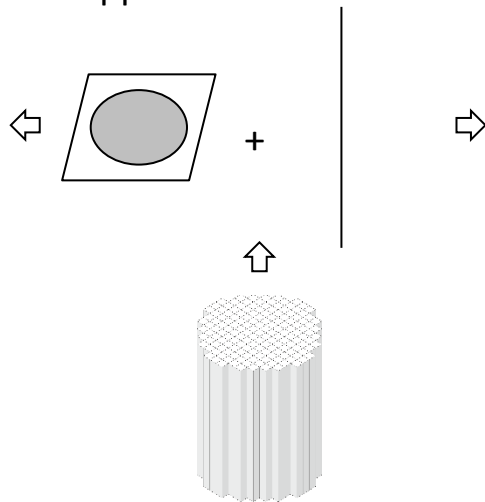
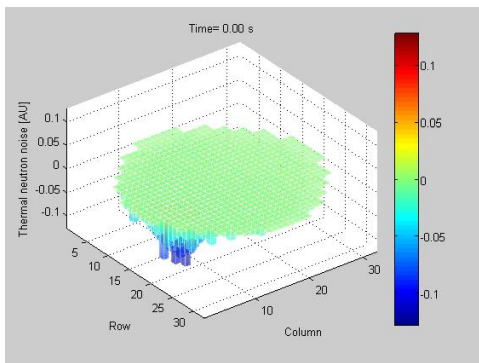
- Use of existing codes or codes specifically developed for noise analysis
- Codes working in either the time- or in the frequency-domain
- Use of coarse mesh or fine mesh approaches

• CORTEX:

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(Chalmers University of Technology)

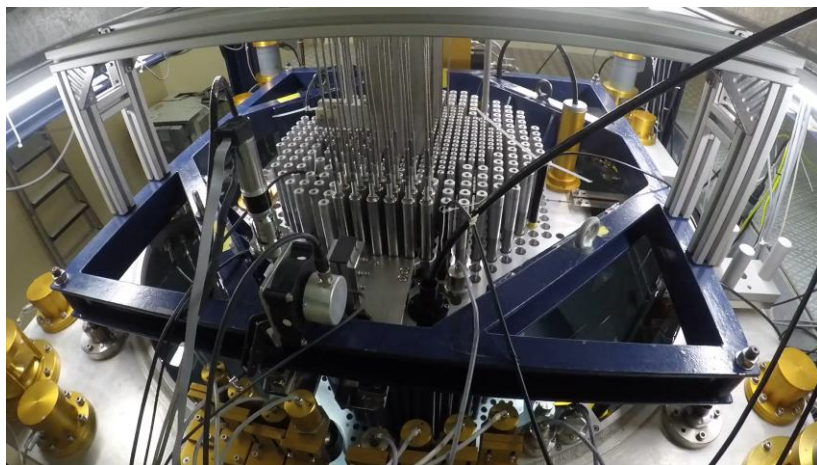
- **CORTEX:**
 - Validation of the modelling capabilities against experiments:
COLIBRI experiments in CROCUS
(@EPFL, Switzerland)

Key objectives and achievements for advanced numerical simulation and modelling

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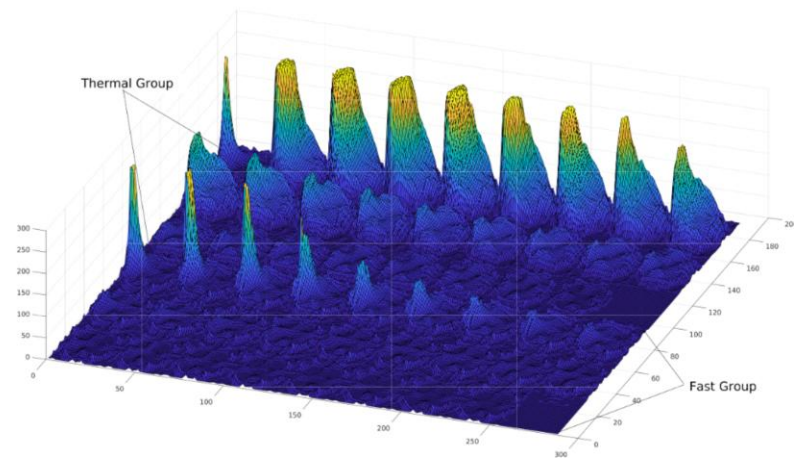
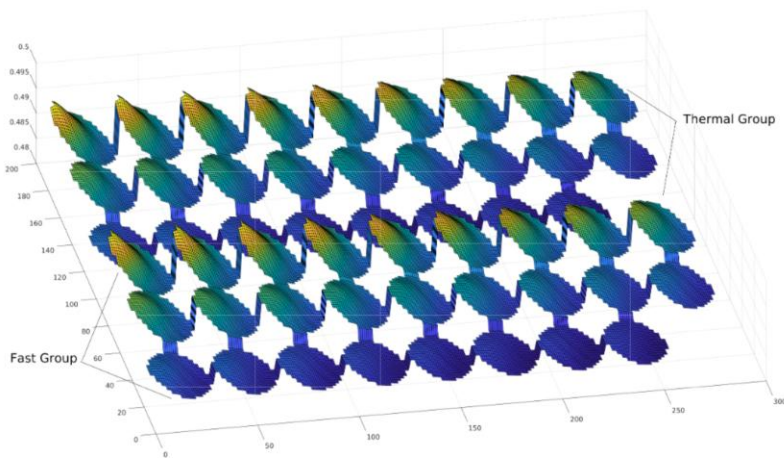
AKR-2 (@TUD, Germany)



- **CORTEX:**

- Inversion of the reactor transfer function using machine learning:

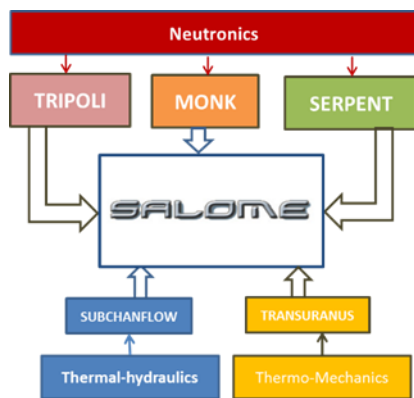
- Detection of abnormal fluctuations and their classification
- Inversion of the reactor transfer function
- Handling of the scarcity of in-core instrumentation
- Handling of intermittences



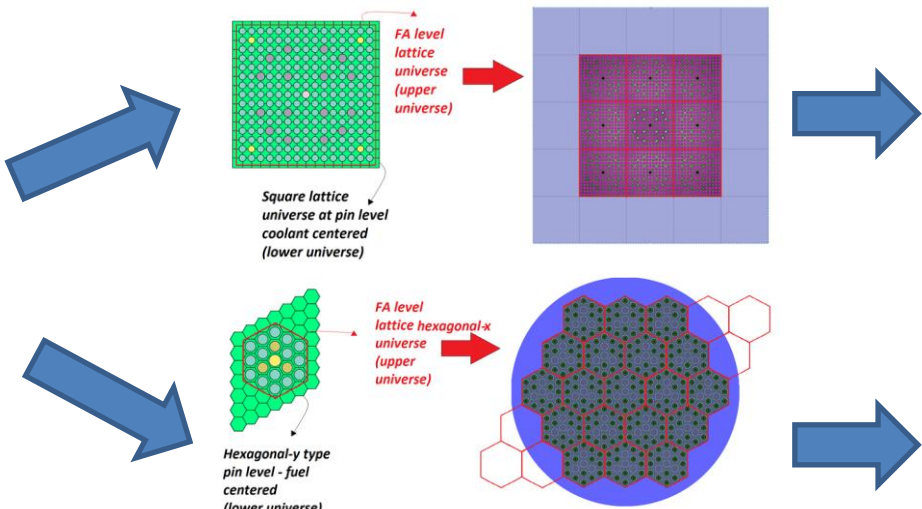
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Key objectives and achievements for advanced numerical simulation and modelling

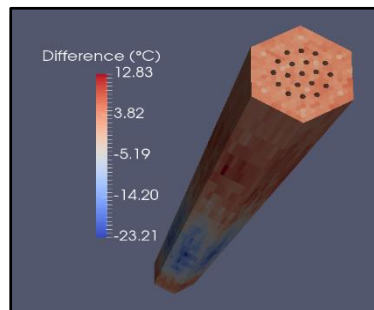
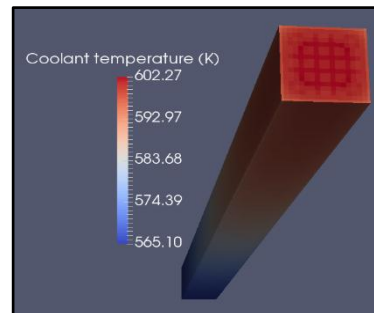
- **HPMC and McSAFE:** Optimal Monte Carlo-thermal-hydraulics coupling:
 - HPMC: Internal/external coupling
 - McSAFE: ICOCO-based coupling and internal master-slave coupling based on Serpent MP-interface with advanced SCF pre-processor, MED coupling library, in-built interpolation (1D, 2D) (SALOME)



McSAFE: Multi-physics Platform tools

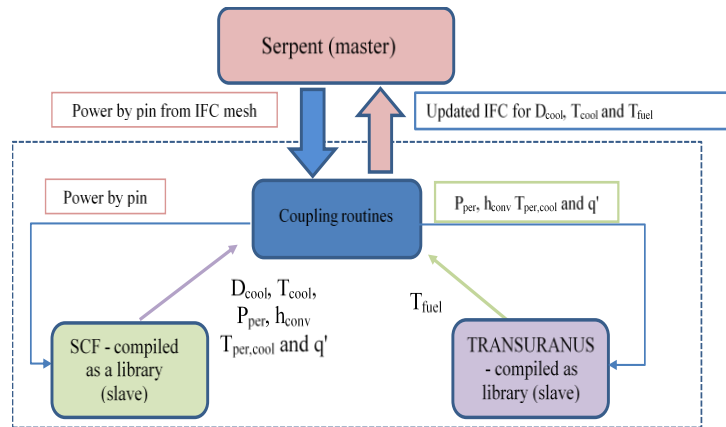


McSAFE: Analysis of cores with square and HEX FAs

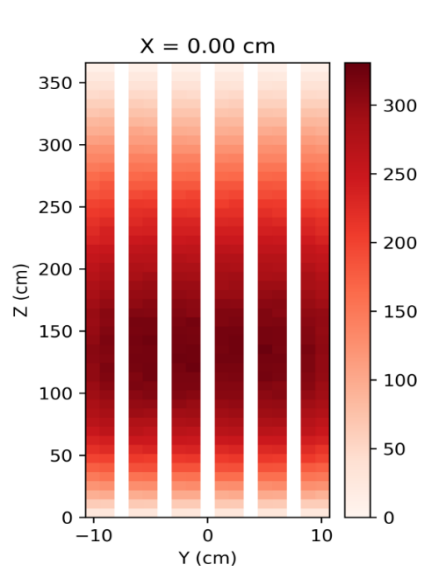


Key objectives and achievements for advanced numerical simulation and modelling

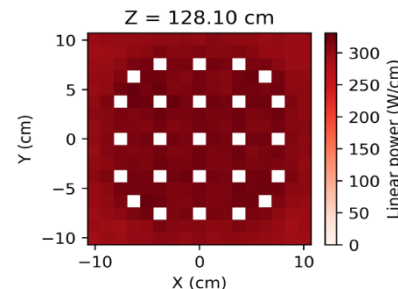
- **McSAFE:** Multiphysics N, TH and TM coupling based on Monte-Carlo:
 - E.g. SERPENT/SUBCHANFLOW/TRANSURANUS: master-slave coupling (one single executable)



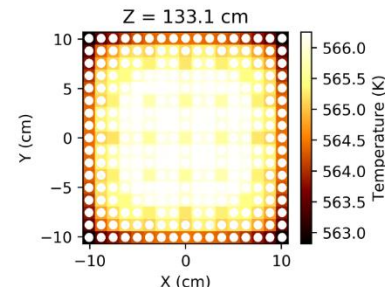
Main coupling Serpent-TU-SCF implementation scheme



FA Vertical Cut: Axial Power



Radial power at max FAX

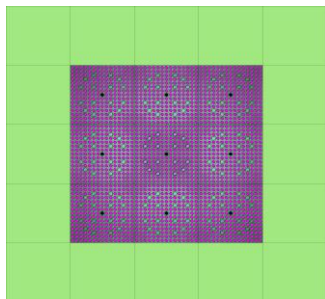


Radial coolant temp at $Z=133.1$ cm

Test case: PWR FA 17x17: PC Xeon 6132 COZ with 28 cores: 90 min

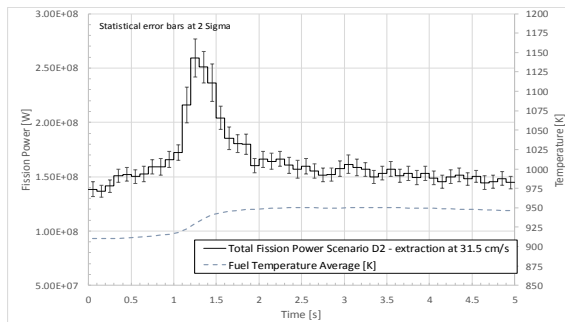
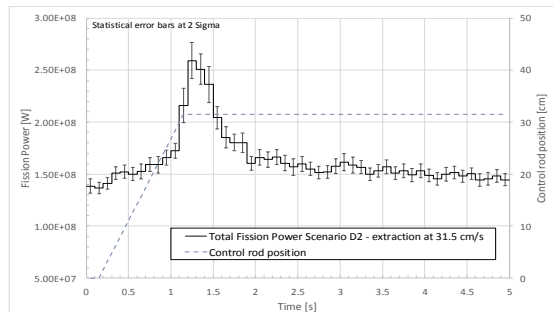
Key objectives and achievements for advanced numerical simulation and modelling

- **McSAFE**: dynamic Monte Carlo capability for transient analysis:
 - New versions of dynSERPENT, dynTRIPOLI, dynMCNP

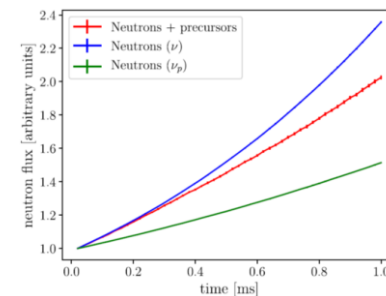
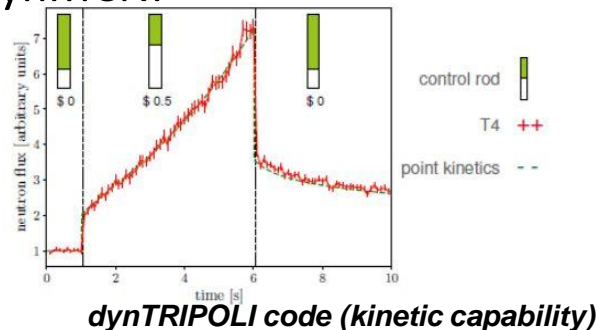


**Minicore 3x3 FA
- Control rod
extraction with
31.5 cm/s**

Demonstration



dynSERPENT/SUBCHANFLOW



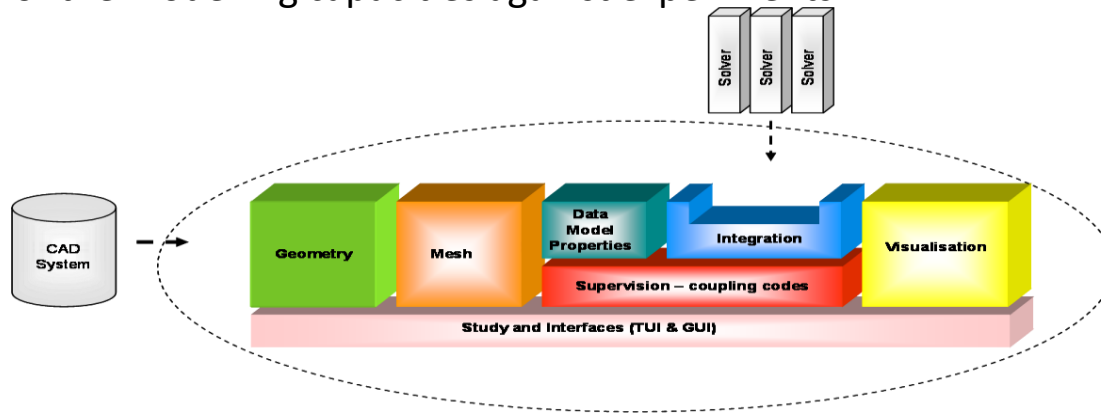
dynTRIPOLI kinetic simulation: role of precursors

Testing: SPERT-III REA

- Red line: TRIPOLI-4 simulation with precursors
- Blue line: TRIPOLI-4 simulation without precursors and ν neutrons created at each fission on average
- Green line: TRIPOLI-4 simulation without precursors and ν_p neutrons created at each fission on average

Key objectives and achievements for advanced numerical simulation and modelling

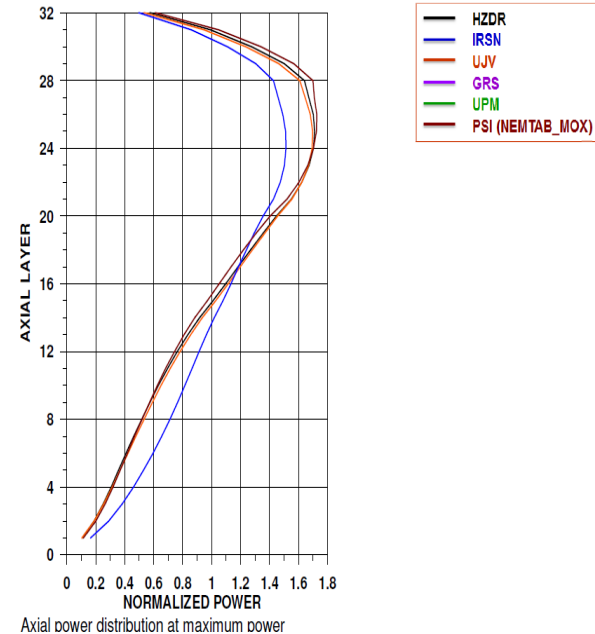
- **NURESAFE:** Enhancement of multi-physics simulation capabilities:
 - Integration of existing codes into the SALOME software platform which provides coupling capacities, uncertainty quantification and standardized users interface
 - Development of advanced 2-phase CFD models in some existing CFD codes
 - Delivery of safety-relevant industry-like applications for LOCA, pressurized thermal shock, MSLB, boron dilution accident, some BWR ATWS
 - Validation of the modelling capacities against experiments



THE SALOME OPEN-SOURCE SOFTWARE PLATFORM

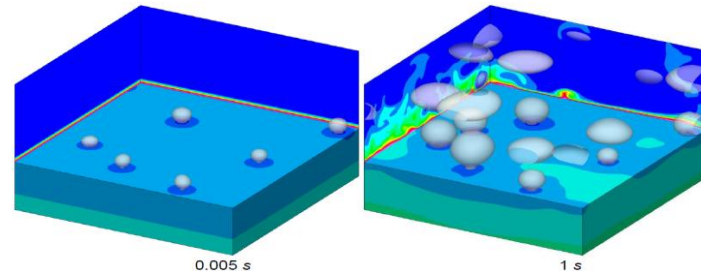
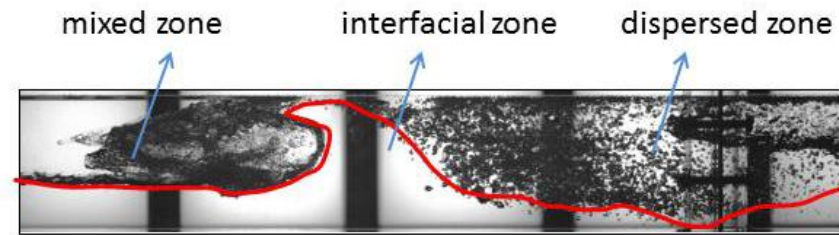
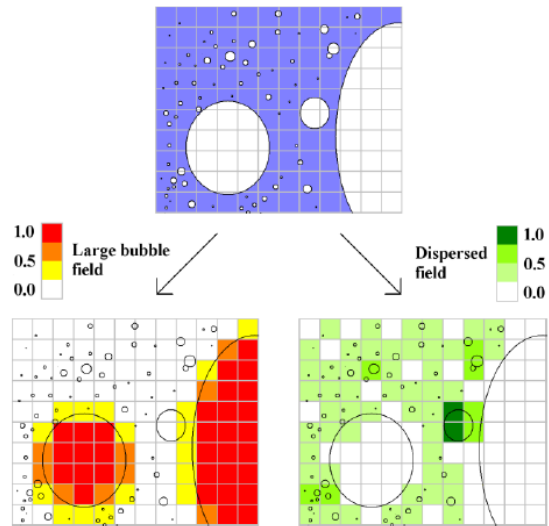
Key objectives and achievements for advanced numerical simulation and modelling

- **NURESAFE:** Development of multi-scale and multi-physics simulation capabilities for safety analyses:
 - 3D code coupling (system, core TH, neutron kinetics), (CFD models, core TH) , (fuel thermomechanics, core TH)
 - MSLB simulation for PWR and VVER (nodal and pin-by-pin modelling)
 - BWR ATWS: simulation of OECD/NEA Benchmark based on the Oskarshamn-2 1999 event
 - Simulation of OECD/NEA BWR Peach Bottom Turbine Trip Benchmark
 - LOCA: coupling system code, CFD and fuel thermomechanics codes for simulation of situations with ballooned fuel rods
 - Pressurized Thermal shock: high fidelity prediction of wall temperature using CFD models
 - BWR TH applications: simulation of steam injection in a pressure suppression pool



Key objectives and achievements for advanced numerical simulation and modelling

- **NURESAFE:** Advancement of the fundamental knowledge in 2-phase thermal-hydraulics:
 - Coupling Interface Tracking models with phase-average models → all flow regimes models
 - DNS and LES modelling of pool and convective boiling
 - DNS and LES modelling of bubbly flow



Key objectives and achievements for advanced numerical simulation and modelling

- **NURESAFE:** Validation of simulation capabilities against experiments:
 - Validation of core neutron kinetics codes: 3D steady state experiments (ZR-6 at KFKI, V1000-LR0 experiments at REZ)
 - ROCOM (HZDR) tests: coolant mixing during MSLB
 - KOZLODUY-6 vessel mixing experiments (MSLB modelling)
 - TOPFLOW PTS (HZDR) steam-water experiments and KAERI CCSF tests: Pressurized Thermal Shock (prediction of mixing of safety injection flow and wall temperature)
 - LOCA: FEBA, ACHILLES, PERICLES experiments (reflooding with ballooned rods)
 - LOCA: MOBY-DICK tests (CEA) for validation of break-flow critical flow prediction
 - PSBT tests: core boiling flow (validation of void fraction prediction by CFD models)
 - PERSEO experiment (ENEA): validation of coupling CFD and TH system codes techniques
 - CHAPTAL experiments (CEA-EDF): modelling of high pressure bubbly flow in a vertical tube
 - Validation of all regimes flow models against CASTILLEJOS experiment
 - And some other experiments.....

Conclusions

- Advancement in the simulation capabilities for **two-phase flows**
- Maturity of the **Monte Carlo**-based methods for **depletion** and **dynamic calculations**
- Truly **multi-physics** and **multi-scale** calculations for **industrial** applications
- Extension of the capabilities to the modelling of **stationary fluctuations**
- Use of **machine learning** for anomaly backtracking

Conclusions

- **Future trends:**
 - **More and more physics** to be accounted for
 - Use of “**hybrid**” methods
 - Increase use of **machine learning** for **predictive modelling**



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