High-fidelity MC-based coupled simulations of LWR cores at pin-level

L. Mercatali, V. H. Sanchez
Karlsruhe Institute of Technology (Germany)

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Content

- Scientific gaps
- McSAFE Technical goals
- McSAFE Main Concept
- McSAFE Structure (WPs & Partners)
- McSAFE Tools
- Summary
Core analysis relies mainly on deterministic neutronic codes (daily work)
- Diffusion codes include multiple approximations (energy, angle, homogenized geometry)
- Pin power approximately reconstructed from 2D lattice calculations
- SP3 and SN solvers are still under development.
  - Currently very time and memory expensive
  - Parallel versions under development

Experimental data at pin level is scarce and not easy to be measured (pin power)

Alternative option:
- Use of MC codes capable of simulating the neutron transport without approximations
- Potential use taking advantage of HPC and parallelization

Innovative solutions needed to pave the way for industry-like applications
McSAFE: Technical Goals

- **McSAFE** is based on innovative ideas developed within the EU 7. FP HPMC Project (High Performance Monte Carlo Core Analysis: 2011-2014)
  - Optimal MC/TH coupling, stable MC-based depletion, **dynamic MC**
  - Many more ideas to simulate whole cores using HPC: UFS, Wieland Shift, Stochastic implicit Euler, …

  *(Proof of concept)*

- **Goal:** Move MC methods towards industrial applications
  - **Generalize N/TH coupling to provided reference solutions**
  - Optimize depletion simulations (stability, CPU)
  - **Analysis of transients such as RIA and others (Safety)**
  - Solve whole cores making use of HPC (improve statistics, reduced CPU)
  - **Validate MC tools using experimental data**

  *(Industry-like applications ➔ McSAFE)*
McSAFE: Time Frame

- Phase 1: 2011 (10)-2014 (9), 7 FP EU HPMC project

- Phase 2: 2017 (9)-2020 (8) → McSAFE
  - Consolidation of the methods for MC-TH coupling
  - Advance validation using exp. Data
  - Consolidate dynamic MC under HPC

- Phase 3: 2020-2023 (9): McSAFE II NOIP
  - Benchmarking of MC with high-fidelity deterministic core solvers for REFERENCE SOLUTIONS
  - Benchmarking of dynamic Monte Carlo solutions with transient deterministic codes for SAFETY CASES (pin level, steady-state and transient)
  - Uncertainty quantifications
  - Extension to Gen-IV reactors, research reactors
A Users Group will be created

Confirmed institutions:
- North Carolina State University (USA)
- National Institute for Nuclear Research (Mexico)
- University of Michigan, (USA)
- University of Illinois, (USA)
- Argonne National Laboratory (USA)
- Canadian Nuclear Laboratories, (Canada)
- Idaho National Laboratory (USA)
- Westinghouse Electric (Sweden)
- SCK-CEN (Belgium)
- IRSN (France)
- POLIMI (Italy)
McSAFE: Main Concept (1)

- MCNP/SUBCHANFLOW Pin-wise Core Simulations

Static full-core simulations: Proof of concept

Safety-relevant and industry-like applications: Local coupling to TH, stable and optimized depletion calculations, etc.

PWR Fuel Assembly → PWR 3x3 FA Cluster → PWR ¼ Core (56 FAs) → McSAFE project
MCNP/SUBCHANFLOW: Direct prediction of local safety parameters

Real core loading!

Computer Resources
- 30 dual socket - 16 cores/node – Total 240 Cores
- 2 MPI x 8 OpenMP per node
- 2.5 GB memory per MPI task
- Convergence: 20 N/TH iterations
- 3.88 days

<table>
<thead>
<tr>
<th>PWR Core Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Temperature</td>
<td>286.85 C</td>
</tr>
<tr>
<td>Exit Pressure</td>
<td>15.45 MPa</td>
</tr>
<tr>
<td>Thermal Power</td>
<td>1034.3 MW</td>
</tr>
<tr>
<td>Highest Clad Temperature</td>
<td>560 K</td>
</tr>
<tr>
<td>Highest Fuel Temperature</td>
<td>1189 K Assembly [4,7], Pin [-5 -7 8]</td>
</tr>
</tbody>
</table>

Number of neutron histories: 1 E9 (kcode equivalent)
Number of tally Volumes: 369 920
Number of pins/Axial nodes: 16184 / 20
Number of TH subchannels: 18 145
TH-Neutronic Mapping: Bijective / Pin level
Fission Source Acceleration: Wielandt Shift
Criticality mode variance reduction: UFS method
Coupled N/TH Scheme Acceleration: Stochastic Accelerated fixed point search
McSAFE: Main Concept (2)

- Transient analysis with MC/Sub-channel Codes

![Diagram of McSAFE project](image)

**Goal:**
Simulation of PWR cores with Dynamic Monte Carlo Methods

- Pin cluster problem
- FA cluster problem
- CR Ejection Transient

**Proof of Principle**

**Industry-like applications**

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Dynamic Monte Carlo: Expected McSAFE Progress Beyond the State of the Art

- Monte Carlo codes will be able to describe reactor-dynamic problems taking into account prompt and delayed neutrons including thermal-hydraulic feedbacks.
- Coupling of neutron and gamma transport in time-dependent calculations
- Determine whether delayed photon heating is relevant in reactor transients
- Improve the capability to simulate control rod movements and other transient initiating events like boron dilution in Monte Carlo simulations coupled to thermal-hydraulics
- Implementation of advanced variance-reduction techniques for delayed supercritical conditions, including limitation of fission chain branching
- External source calculation in dynamic simulations
- Dynamic Monte Carlo codes open the doors for safety-related simulations of any kind of reactor designs e.g. research reactors, SMR, LWR (Gen-II, Gen-III) and Gen-IV systems
- Direct prediction of local safety parameters for transients (e.g. REA, boron dilution, MSLB), will be feasible
WP4: Development of Dynamic Monte Carlo Methods for Transients Analysis

Pave the way for the analysis of industry-relevant transients e.g. RIA, ATWS or MSLB

Technical goals:

- Development of time-dependent dynSerpent-SCF e.g. implementation of methods to account for the prompt neutron and gamma heat deposition in the coolant
- Development of time-dependent dynTripoli-SCF or -FLICA4
- Development of time-dependent dynMCNP-SCF
- Variance reduction for MC-codes with dynamic capability to improve the efficiency of time-dependent MC solutions e.g. Uniform Fission Sites (UFS)
- Methods for optimal parallel scalability of MC-TH codes for dynamic simulations to take profit of massively parallel environments in the frame of industry-like applications.
- Verification of developed tools on 3x3 pin cluster or PWR minicore (3x3 FA)
dynMCNP: Demonstration Calculation

- CR shifted (z=49cm) in $t=0.3$ sec.
- 20 time intervals of 0.1 s. (movement of CR starts at $t=0.2$ s.)
- 5 nodes, 7 cores/node (MPI/openMP)
- Computing time: $\sim 2.5$ days (target time: $\sim 1$ day)

- TRIPOLI/SCF: 28 cores (one week)
McSAFE: Numerical Tools and Coupling approaches

- Focus on the further development of European MC, TH and TM codes and on the coupled systems already developed during the 7FP EU project HPMC to make possible industry-like simulations of both fuel depletion with stable and accurate depletion methods and LWR transients (safety-related) with the developed dynamic MC solutions

<table>
<thead>
<tr>
<th>Methods</th>
<th>Monte Carlo (MC)</th>
<th>Thermal Hydraulic (TH)</th>
<th>Thermo Mechanics (TM)</th>
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</thead>
<tbody>
<tr>
<td><strong>Static MC-TH</strong></td>
<td>TRIPOLI</td>
<td>SCF, FLICA, TRUST</td>
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<td></td>
<td>SERPENT</td>
<td>SCF, COSI</td>
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<td>MCNP</td>
<td>SCF</td>
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<td>MONK</td>
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<tr>
<td><strong>Static MC-TH with depletion</strong></td>
<td>TRIPOLI</td>
<td>SCF, FLICA, TRUST</td>
<td>TU, FINIX, TU</td>
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<td>SERPENT</td>
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<tr>
<td><strong>Dynamic MC-TH</strong></td>
<td>DynTRIPOLI</td>
<td>SCF</td>
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<td>DynMCNP</td>
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<tr>
<td><strong>Dynamic MC-TH-TM</strong></td>
<td>DynTRIPOLI</td>
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McSAFE: Concept for Validation

- High-fidelity coupled MC-TH simulations as reference solutions

Role of High Fidelity Monte Carlo Simulations

- Diffusion + Pin Power Reconstruction
- Experimental data
- PWR FA
- PWR 3x3 FA Cluster
- DYN3D-PPR: NURISP PWR Boron Dilution Benchmark
- SP3 Transport/Subchannel
- DYNSUB: 3D Avg. Pin Power Density [W/cm³]
- OR
- Monte Carlo simulations with TH Feedback can provide Reference Solutions
- Code-to-code benchmarking

MCNP5/SUBCHANFLOW: High Fidelity Simulation at pin level

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Newly available plant data in the frame of international benchmarks or in the single initiatives by utilities (e.g. PreussenElektra or CEZ) pave the way for the validation of the improved capability of multi-physics tools based on Monte Carlo codes regarding e.g. local safety parameters, depletion, and fuel behaviour.

<table>
<thead>
<tr>
<th>Plant Data</th>
<th>Static MC-TH Problem</th>
<th>Static MC-TH-TM Depletion Problem</th>
<th>Dynamic Problem</th>
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<tbody>
<tr>
<td><strong>VVER-1000</strong></td>
<td>TRIPOLI</td>
<td>SERPENT/SCF/TU</td>
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<td>MCNP/SCF</td>
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<td><strong>PWR Konvoi</strong></td>
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<td>SERPENT/SCF/TU</td>
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<td><strong>SPERT III E REA</strong></td>
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McSAFE: Expected Outcome

- The project will deliver improved and validated high-fidelity numerical simulation tools that can be used by different end-users (industry, regulators, research centres, etc.) to provide reference solutions to deterministic codes for safety demonstration.

- The McSAFE tools are essential to design reactor systems with improved safety features keeping sufficient safety margins. The project will reinforce the European leadership’s nuclear engineering methods to better assess the safety of NPP and make NPP operation more flexible while keeping high safety standards.

- The McSAFE calculation schemes are applicable to any reactor type, current or future, provided the thermal-hydraulics codes are capable of dealing with the specific reactor type. For future nuclear reactors verification of design calculation methods is even more important as reference data are not available.