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

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Scientific Gaps

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- **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

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- **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

McSAFE: Structure & Partners

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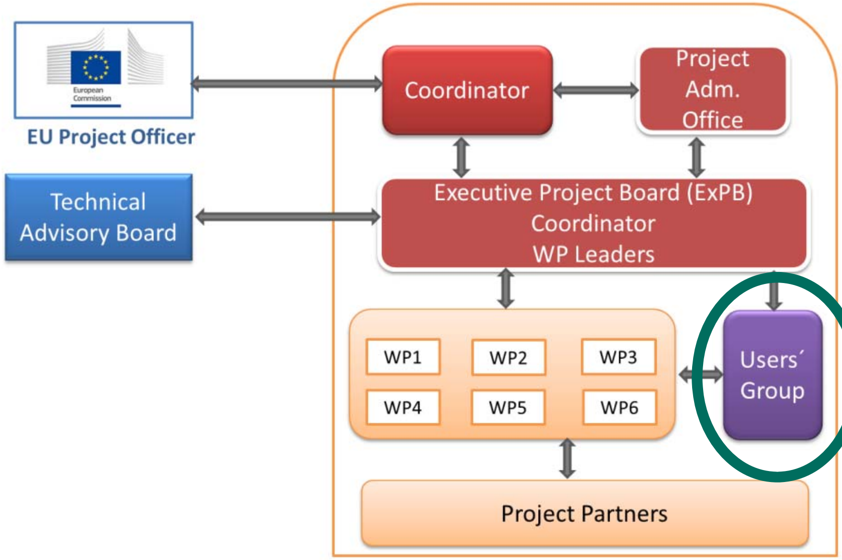
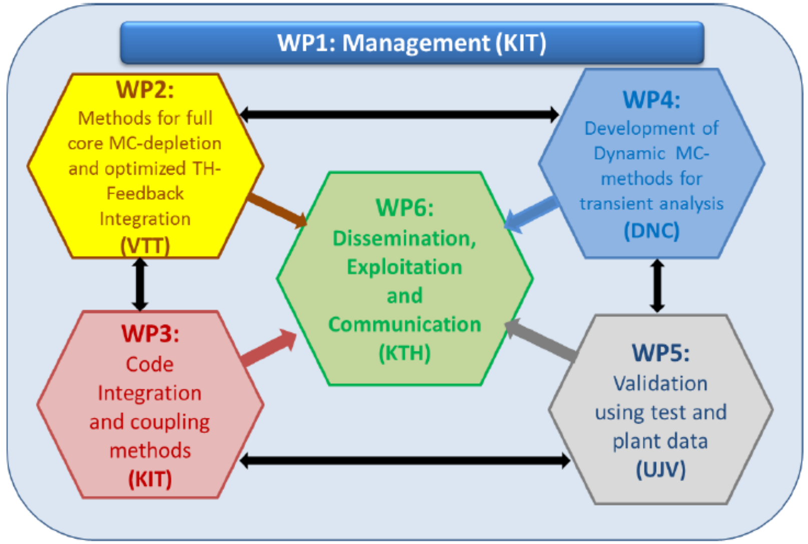




RESEARCH

INDUSTRY

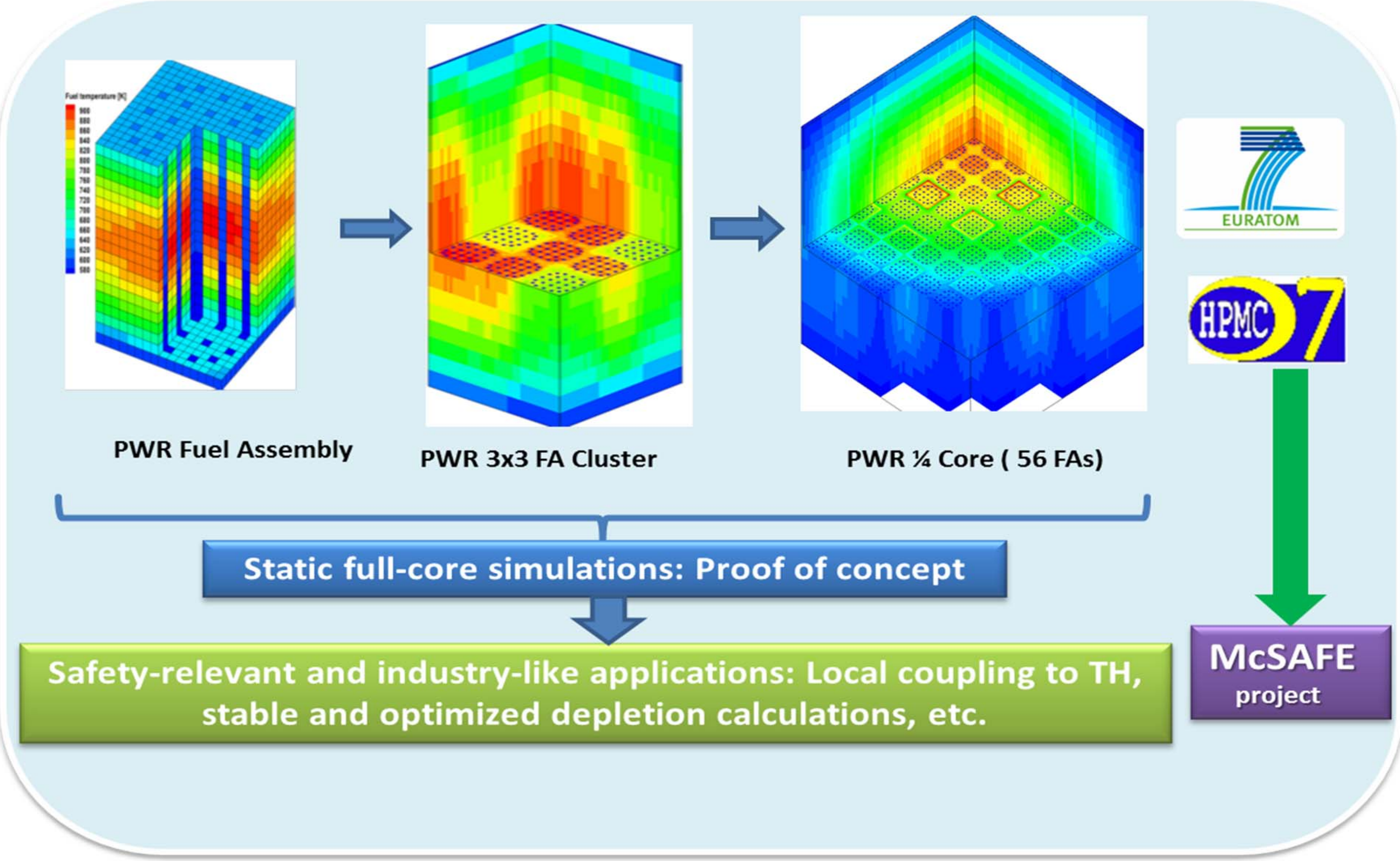
A Users Group will be created

Confirmed institutions:

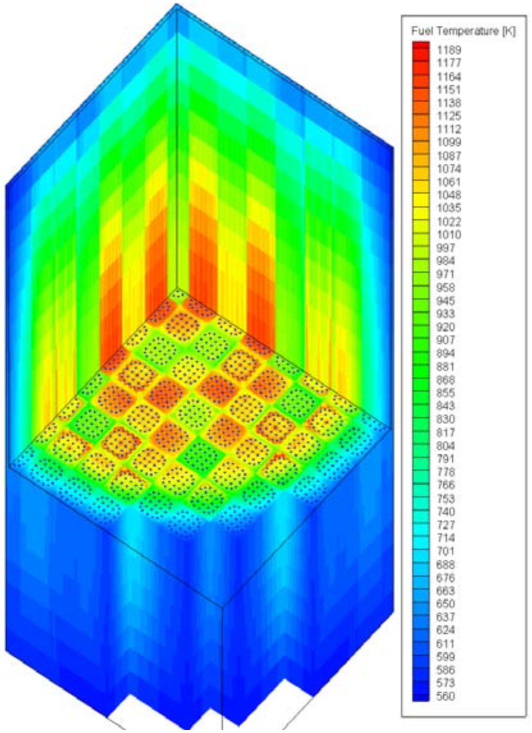
- **North Carolina State University (USA)**
- **National Institute for Nuclear Research (Mexico)**
- **University of Michigan, (USA)**
- **University of Illinois, (USA)**
- **Argonne National Laboratory (USA)**
- **Canadian Nuclear Laboratories, (Canada)**
- **Idaho National Laboratory (USA)**
- **Westinghouse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

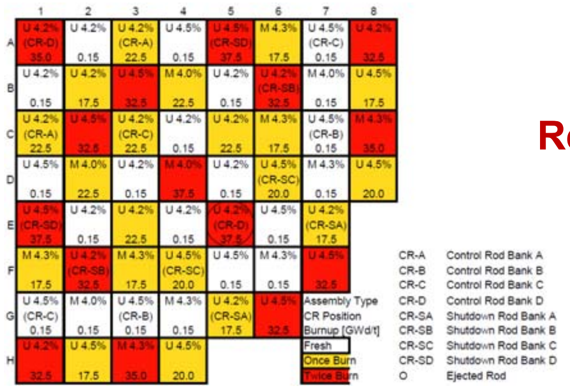
McSAFE: Main Concept (1)

- MCNP/SUBCHANFLOW Pin-wise Core Simulations

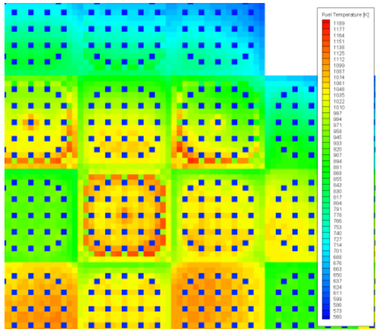


MCNP/SUBCHANFLOW: Direct prediction of local safety parameters





Real core loading!



Computer Resources

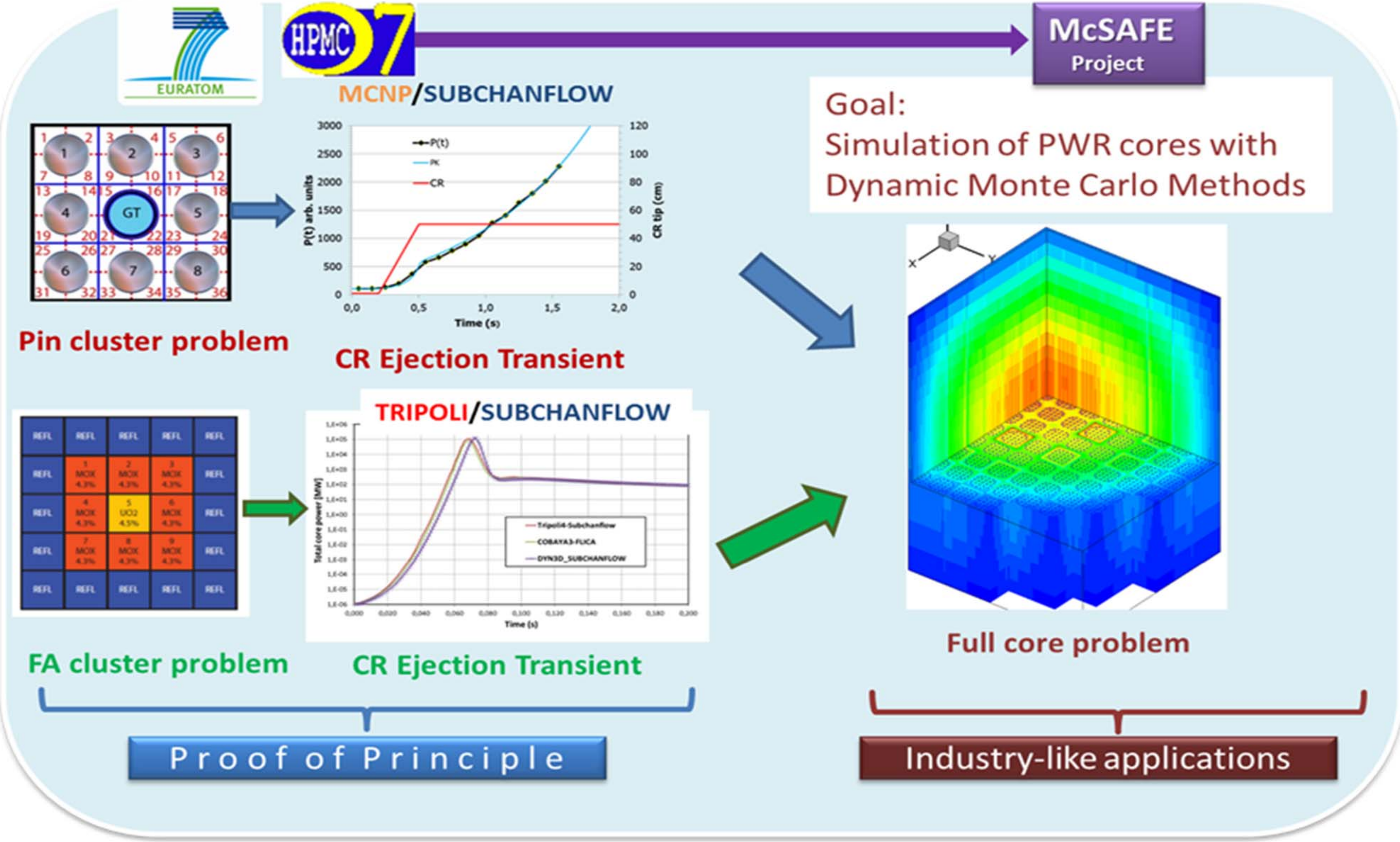
- 30 dual socket - 16 cores/node – Total 240 Cores
- 2 MPI x 8 OpenMP per node
- 2.5 GB memory per MPI task
- Convergence: 20 N/TH iterations
- 3.88 days

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

PWR Core Parameter	Values
Inlet Temperature	286.85 C
Exit Pressure	15.45 MPa
Thermal Power	1034.3 MW
Highest Clad Temperature	560 K
Highest Fuel Temperature	1189 K Assembly [4,7], Pin [-5 -7 8]

McSAFE: Main Concept (2)

- Transient analysis with MC/Sub-channel Codes



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

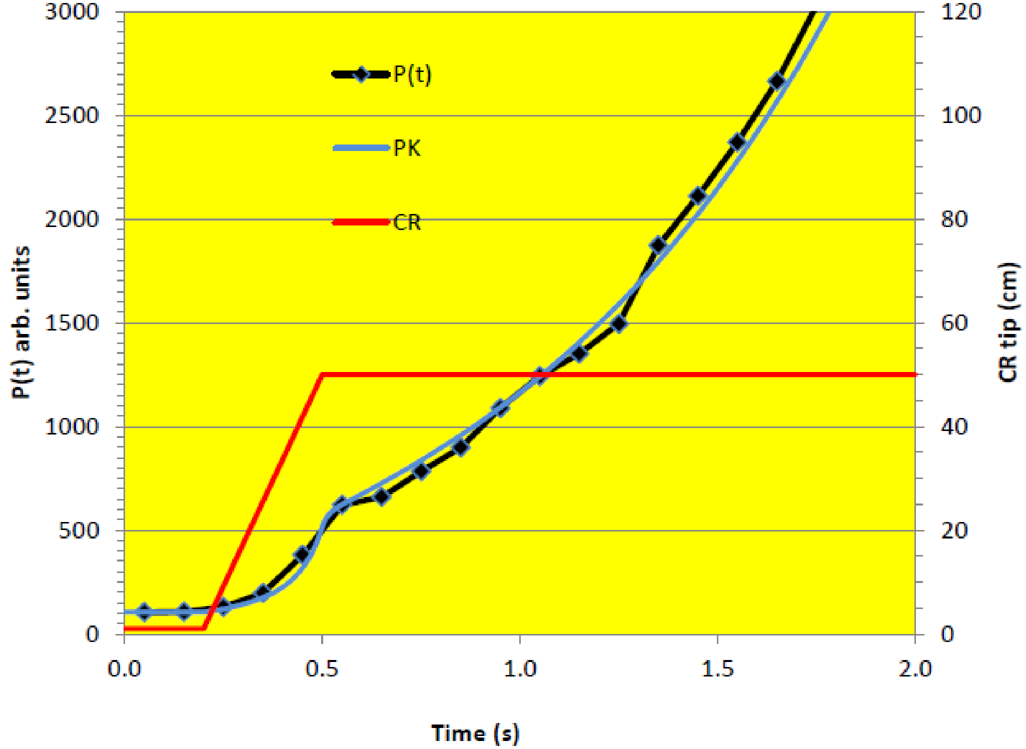
Pave the way for the analysis of **industry-relevant transients** e.g. RIA, ATWS or MSLB

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

PWR 3x3 FA



- **dynMCNP:**
  - **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:~2.5 days (target time: ~ 1 day)**
- **TRIPOLI/SCF: 28 cores (one week)**

McSAFE: Numerical Tools and Coupling approaches

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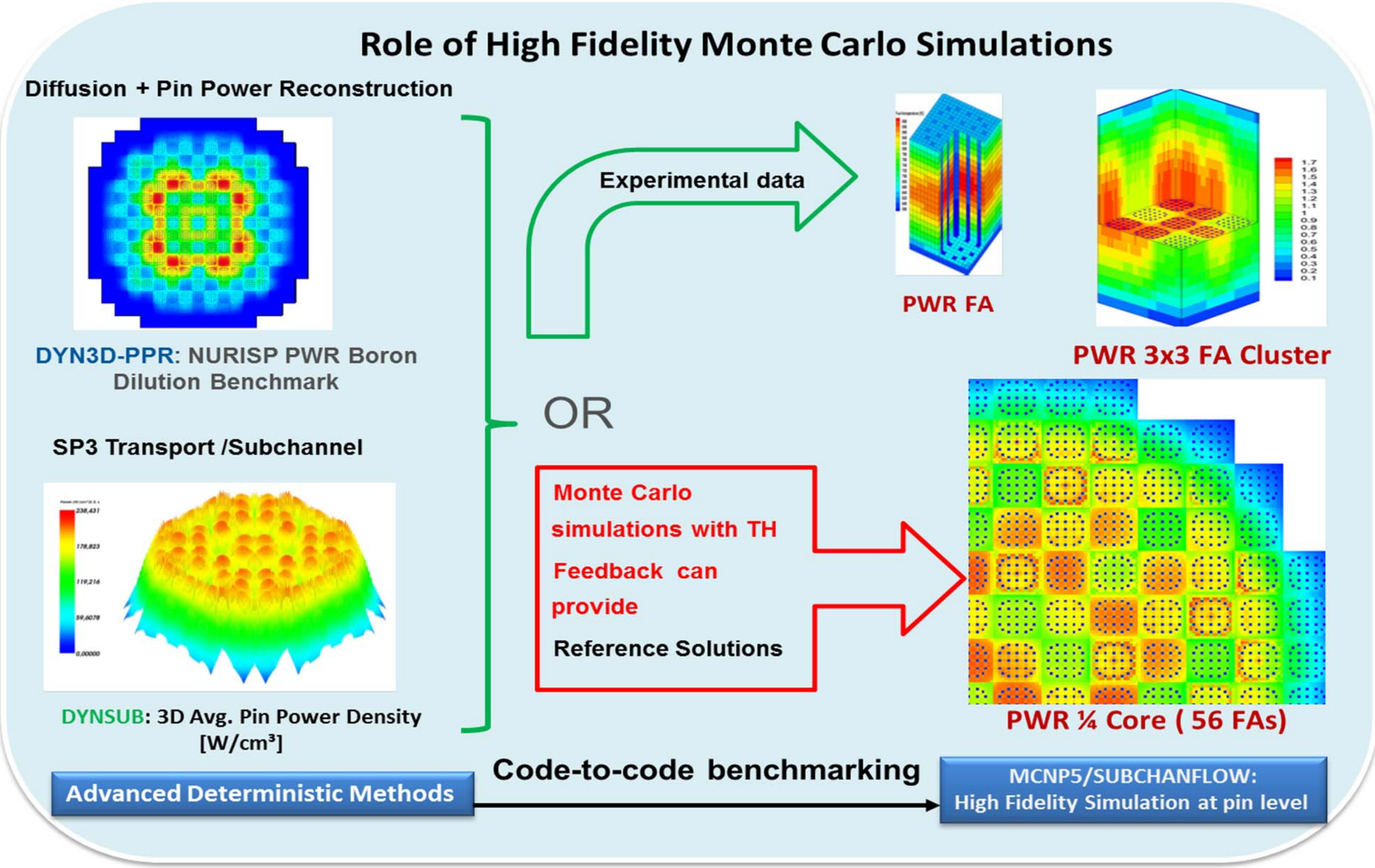
- Focus on the further development of European MC, TH and TM codes and on the coupled systems already developed during the 7FP EU project HPMC to make possible industry-like simulations of both fuel depletion with stable and accurate depletion methods and LWR transients (safety-related) with the developed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

Methods	Monte Carlo (MC)	Thermal Hydraulic (TH)	Thermo Mechanics (TM)
Static MC-TH	TRIPOLI SERPENT MCNP MONK	SCF, FLICA, TRUST SCF, COSI SCF SCF	
Static MC-TH with depletion	TRIPOLI SERPENT MONK	SCF, FLICA, TRUST SCF, COSI SCF	TU TU, FINIX TU
Dynamic MC-TH	DynTRIPOLI Dyn SERPENT DynMCNP	SCF SCF, COSI SCF	
Dynamic MC-TH-TM	DynTRIPOLI DynSERPENT	SCF, FLICA, TRUST SCF, COSI	TU TU, FINIX

McSAFE: Concept for Validation

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



McSAFE: WP5 – Validation Matrix

- 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

Plant Data	Static MC-TH Problem	Static MC-TH-TM Depletion Problem	Dynamic Problem
VVER-1000	**TRIPOLI** **SERPENT/SCF** **MCNP/SCF**	**SERPENT/SCF/TU**	
PWR Konvoi	**TRIPOLI/SCF** **SERPENT/SCF** **MCNP/SCF**	**SERPENT/SCF/TU**	
SPERT III E REA			**DynTRIPOLI/SCF** **DynSERPENT/SCF** **DynMCNP/SCF**

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