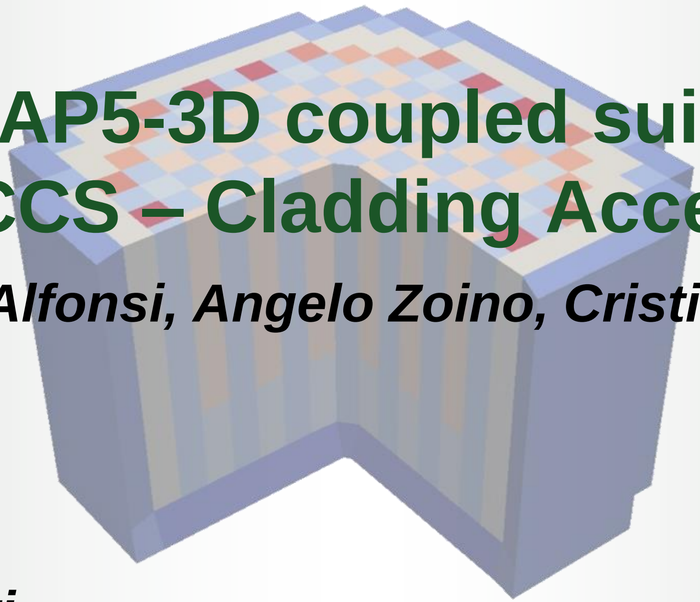
U.S. DEPARTMENT OF ENERGY | Nuclear Energy

IRUG meeting August 2015



PHISICS/RELAP5-3D coupled suite for Industry Application: ECCS – Cladding Acceptance Criteria

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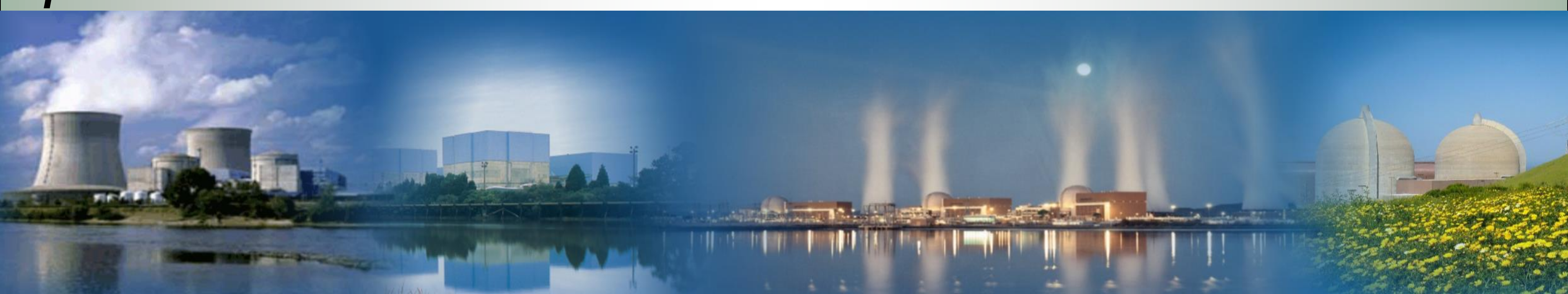
Speaker: Cristian Rabiti

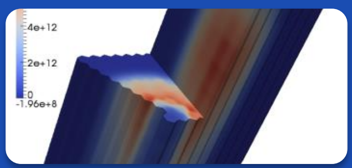


Outline

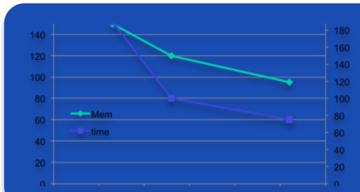
- **PHISICS-RELAP5-3D overview**
- **Industrial applications:**
  - ECCS – Cladding acceptance criteria
- **Developed capabilities:**
  - Extension of PHISICS fuel management tool
  - Material movement criticality search (Control Rod criticality search)
- **Results**
- **Conclusions**

PHISICS: Software purposes

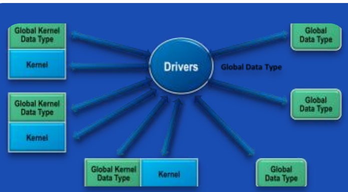
Parallel and **H**ighly **I**nnovative **S**imulation for the **I**NL **C**ode **S**ystem (PHISICS) principal purposes are:



Provide state of the art simulation capability to reactor designers, especially for advanced reactors such as Generation IV systems



Provide an optimal trade off between needed computational resources and accuracy



Simplify the independent development of modules by different teams and future maintenance

PHISICS: Modules

INSTANT
Intelligent Nodal and Semi-structured Treatment for Advanced Neutron Transport

MIXER

MRTAU
Multi-Reactor Transmutation Analysis Utility

CRITICALITY

TIME INTEGRATOR

RELAP5-3D coupling

Shuffling module

PARALLEL (MPI) ENVIRONMENT

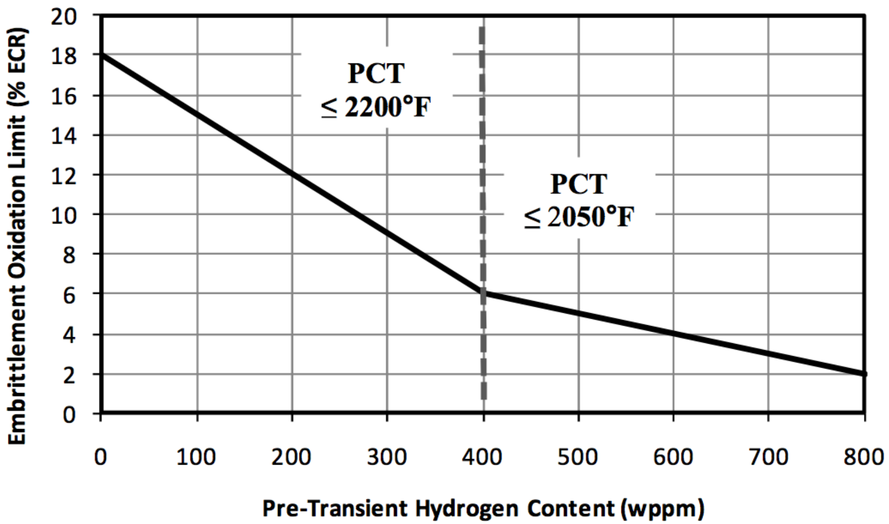
Industrial Applications: ECCS – Cladding acceptance criteria

- **Under the RISMC/RIMM work scope (LWRS program) one of the identified possible forthcoming issues is:**
  - The Nuclear Regulatory Commission (NRC) is currently considering a revision of the requirements in 10 CFR 50.46C rules, focused on the ECCS rule in LOCA scenarios;
- **The new approach modifies the analysis strategy in order to also take into account the effects of the burn-up rate;**
- **The max allowable clad temperature and oxidation of the cladding are function of the burn up**
- **The core history is therefore needed to identify the limiting case.**

Simulation Needs

To compute the burn up at any point in the reactor life it is necessary to simulate:

- Coupled TH core depletion
- Boron evolution for each cycle
- Multiple fuel cycle with specific loading pattern and fuel enrichments
- Reactor maneuver simulation
- Concatenating multiple execution modes



Some Work Was Needed

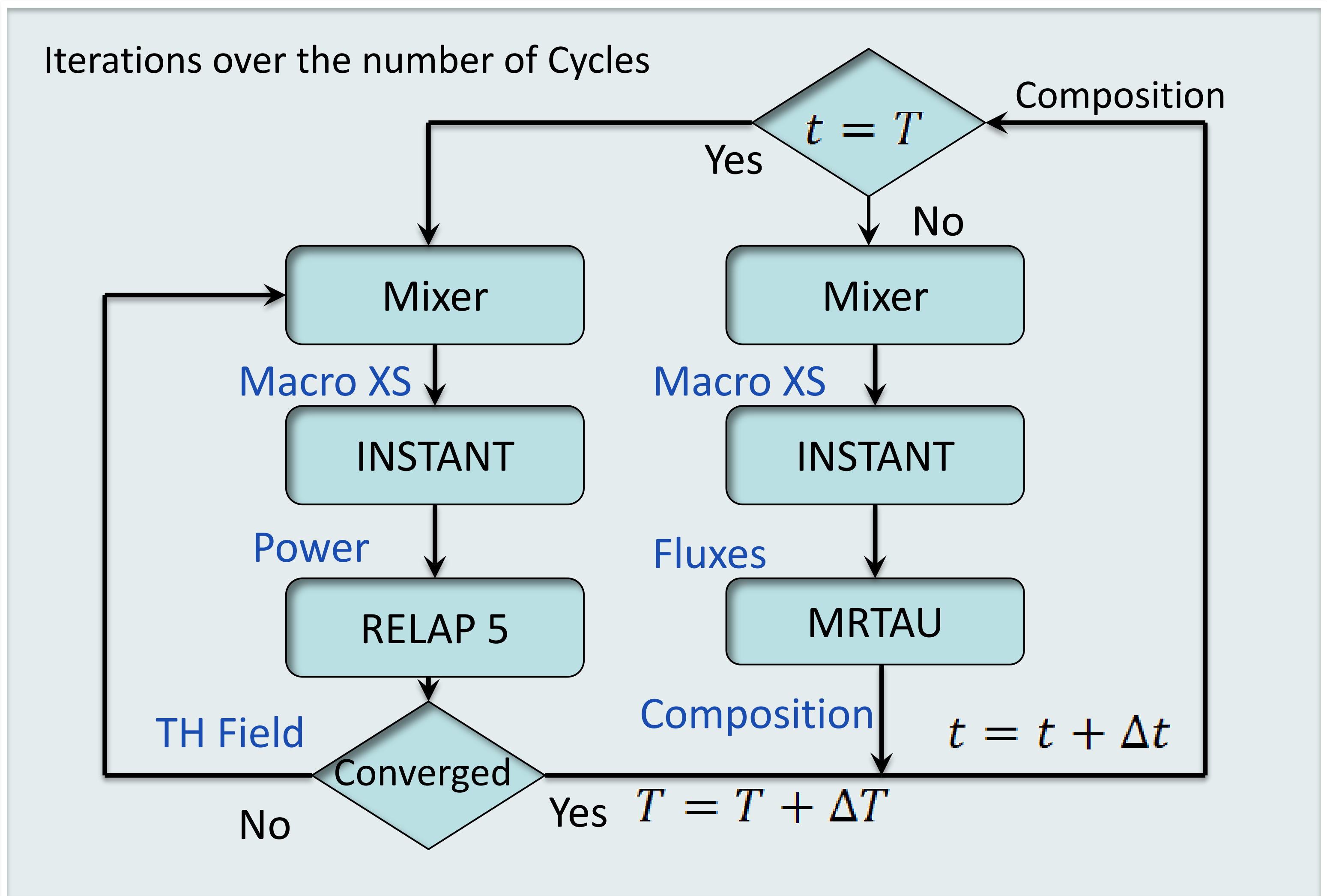
- **Improve the Fuel Management tool (shuffling module) in order to:**
  - Simplify the input syntax for multi-cycle analysis
  - MPI implementation

- **Material Movement Criticality search:**
  - Extended the Criticality search module in order to find the critical position of material (for example, control rods)

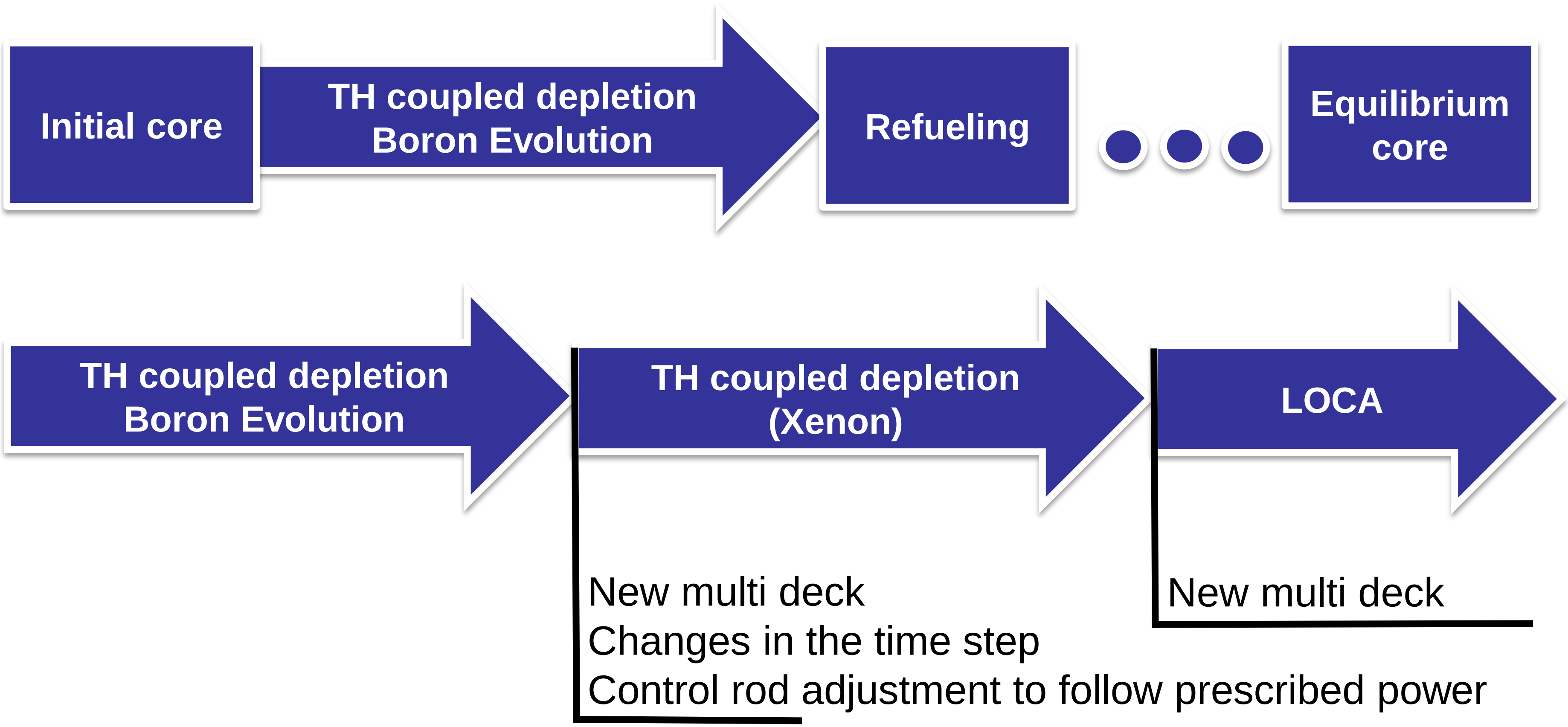
- **RELAP5-3D Multi-Deck capability:**
  - In conjunction with Dr. Mesina(RELAP5), the RELAP5 multi-deck has been debugged and made functional for any number of decks to be run in sequence

Depletion Time Evolution Coupled with RELAP5-3D

- **Calculation scheme used:**



Calculation Flow



Core Design Reference Plant

- The reactor design has been based on a typical Westinghouse 4-loop PWR with thermal rated power of 3411 MW
- The modeling of this reactor is based on the “Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS).”
- The LOCA accident scenario would be initiated from equilibrium cycle conditions.
- The reactor evolution needs to be followed for several operational cycles, until reaching a “reference” equilibrium cycle.
- In this study, we assume the equilibrium cycle is reached after the 10th reloading (the 11th cycle is considered to be equivalent to the equilibrium cycle).

Core Design Plant Characteristics

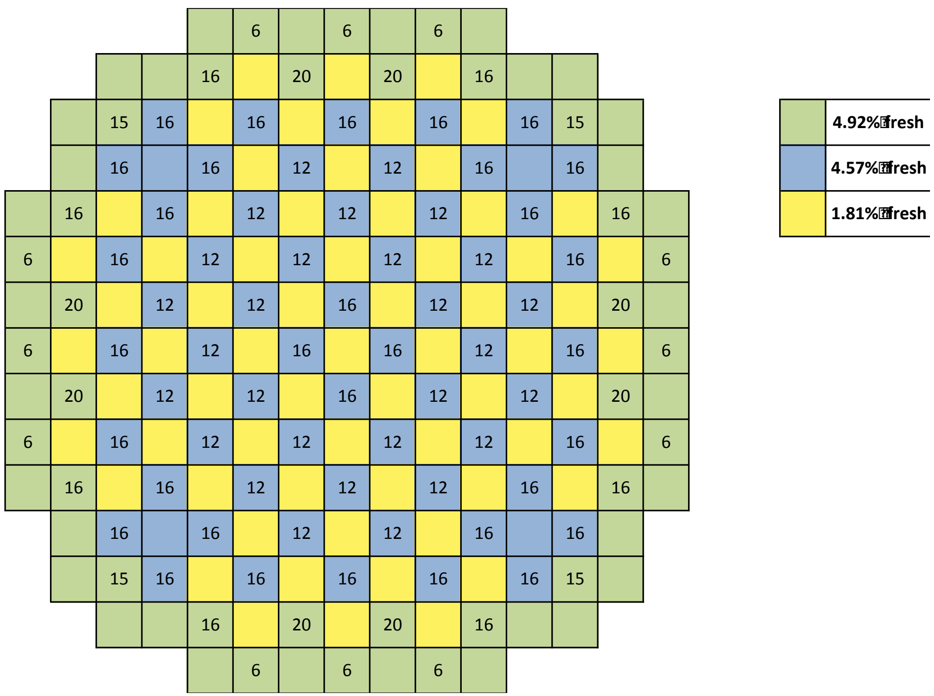
- **15x15 assemblies, 18 axial levels**
- **17 different assembly types**
  - **3 different enrichments**
  - **burnable absorber**
  - **control rods**
- **1 depletion zone by assembly**
- **RELAP5-3D: 1 core channel by assembly**
- **Total ~5,000 computational zones**

Cross Sections	Data
# Energy Groups	8
# Isotopes	~ 300
# Tracked Isotopes	~ 200
# Tabulation Dimensions	4
# XS Libraries	64
Total Tabulation Points	102

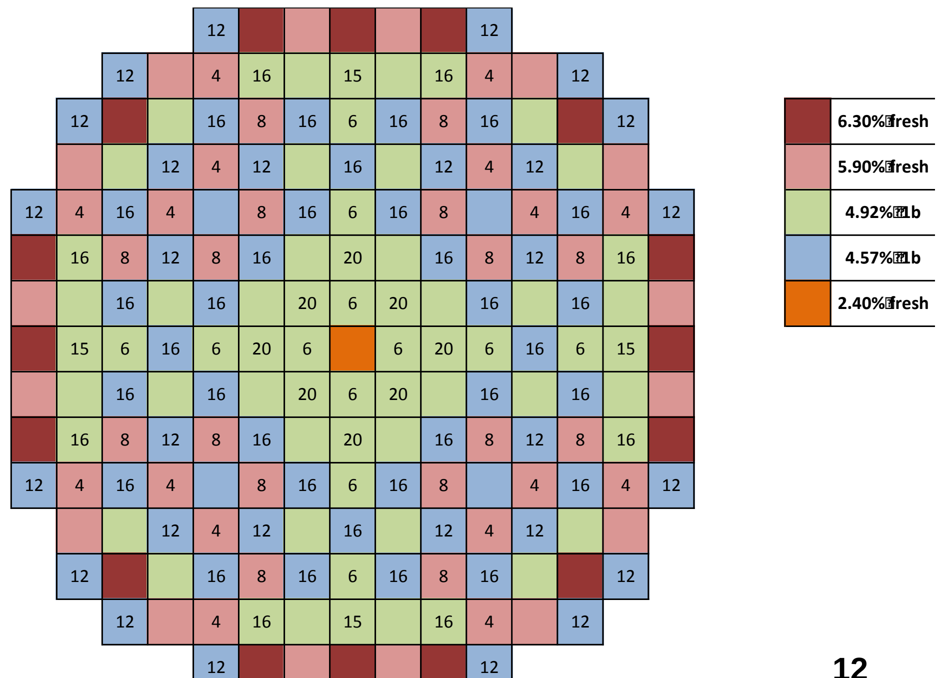
Multi-Cycle Fuel Load Patterns

- **10 Cycles simulated. Fuel Patterns:**
  - 1st and 2nd cycle based on BEAVERS benchmark (High Leakage)
- **Enrichments have been adjusted to reach the target of 18 month/cycle**

1st Cycle

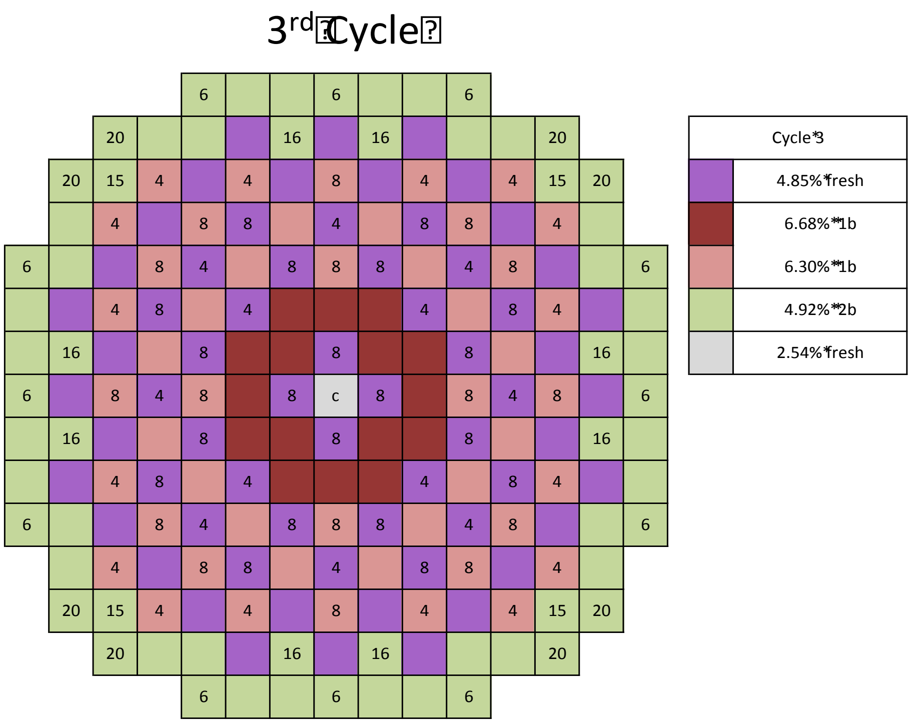


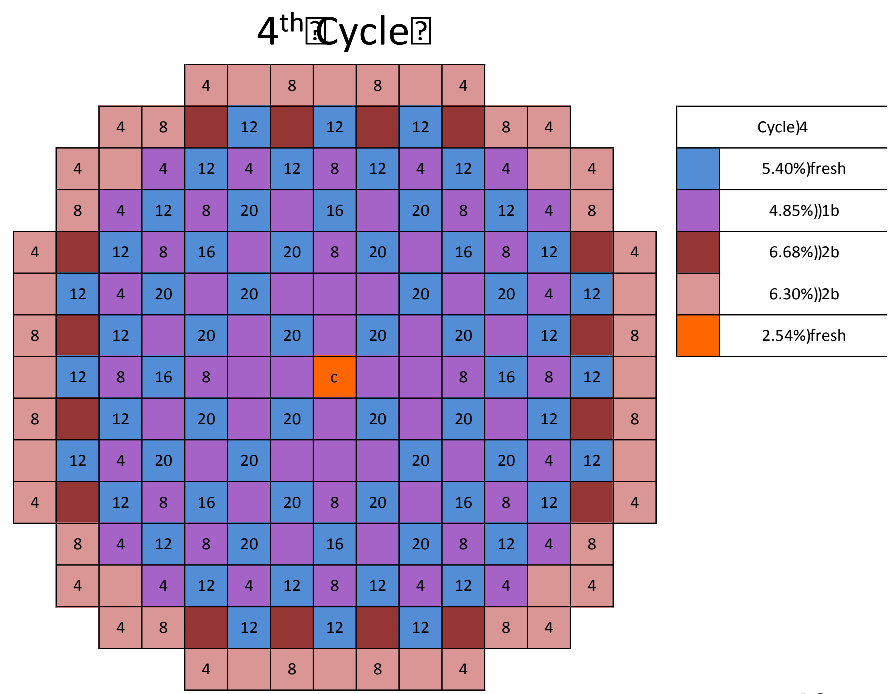
2nd Cycle



Multi-Cycle Fuel Load Patterns (cont.)

- **Fuel Patterns:**
  - 3rd and 4th cycle internally developed:
    - *3rd ➔ transition from High to Low Leakage (Intermediate Step)*
    - *4th ➔ Low Leakage (still influenced from the previous cycles' fuel batches)*

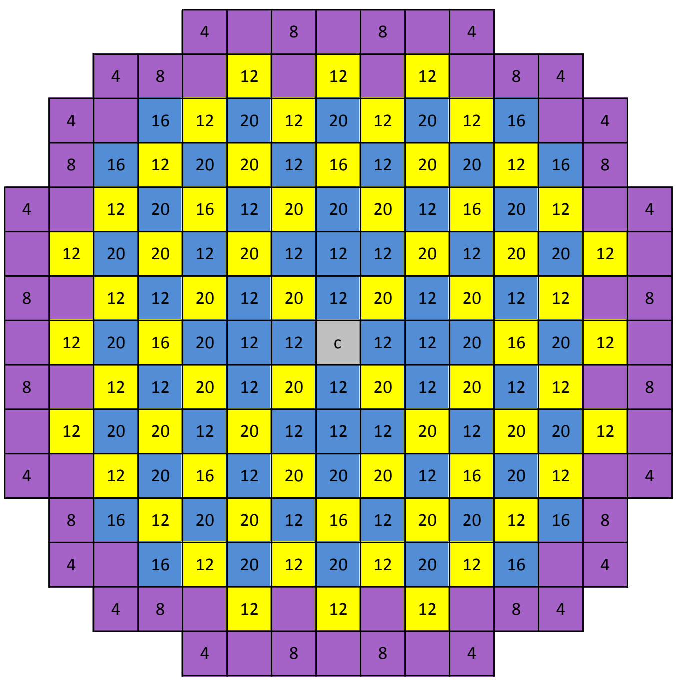




Fuel Patterns:

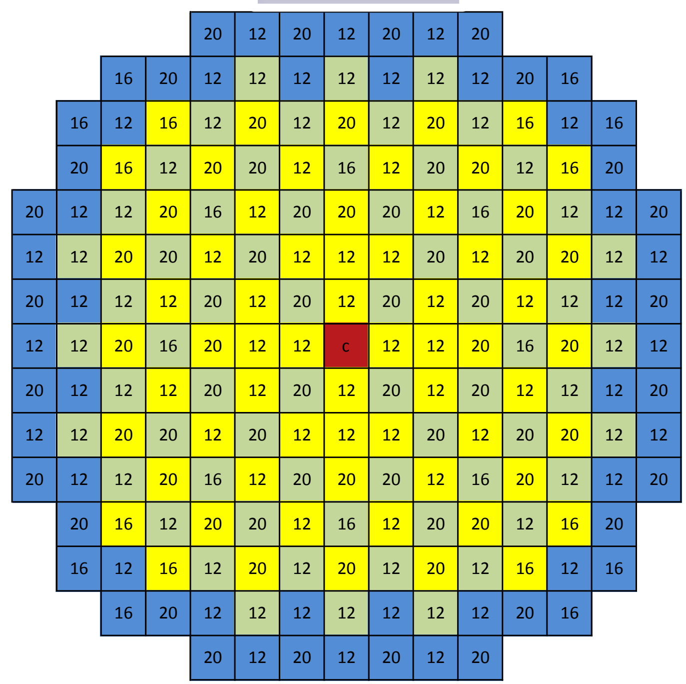
- 5th and nth cycle internally developed:
  - *5th ➔ Low leakage (last cycle influence from the transition fuel patterns)*
  - *6th to nth ➔ Low Leakage pattern (10th considered at the equilibrium)*

5th Cycle



	Cycle 5
	5.40% fresh
	5.40% 1b
	4.85% 2b
	2.54% fresh

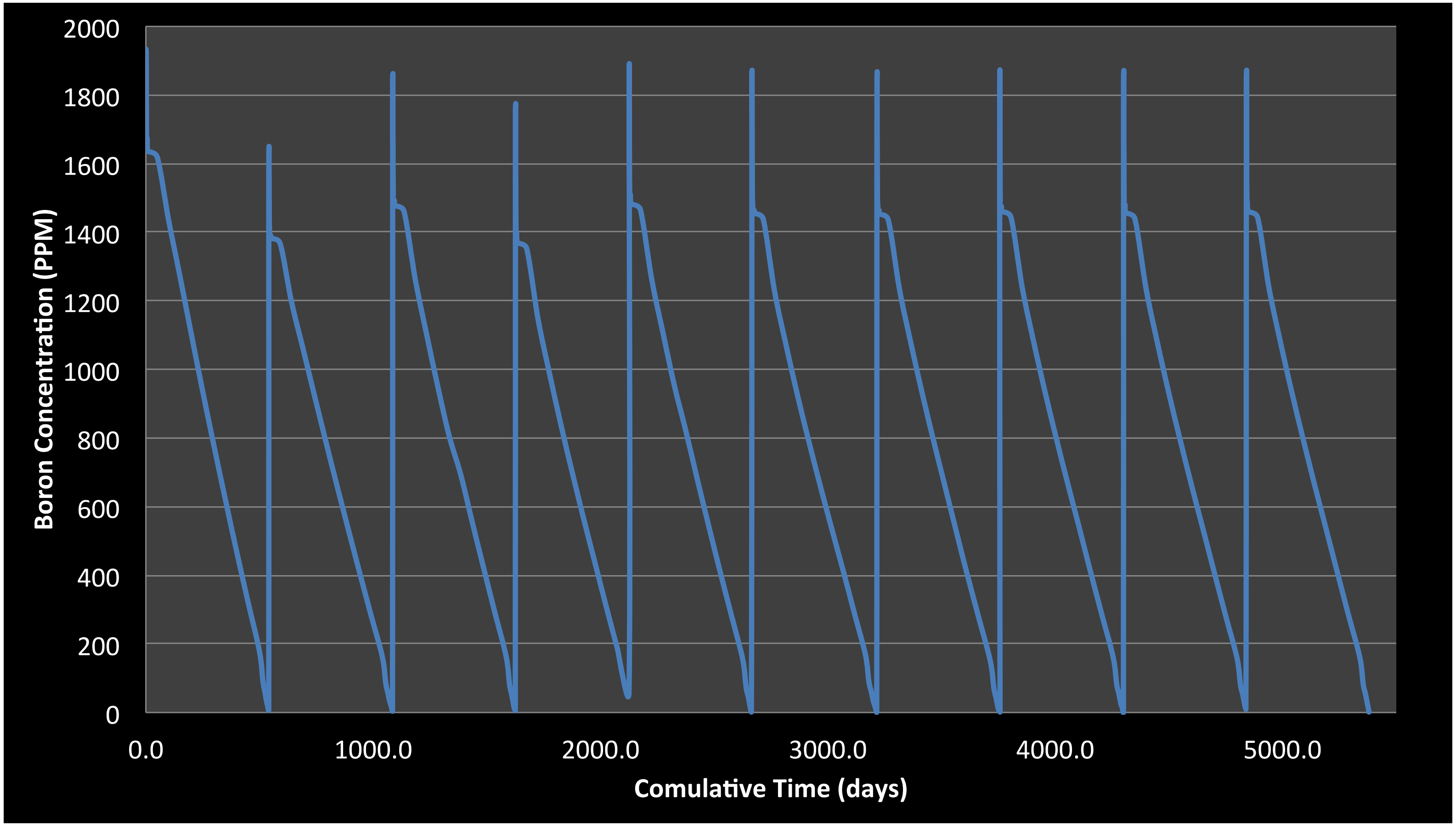
nth Cycle ← Equilibrium



	Cycle n
	5.40% fresh
	5.40% 1b
	5.40% 2b
	2.54% fresh

Boron Evolution

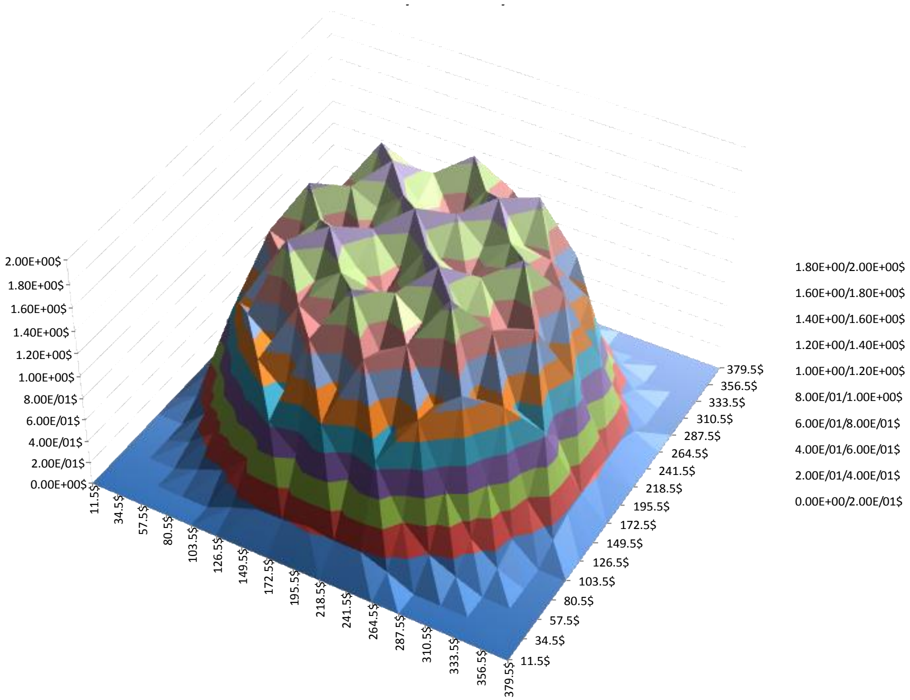
- The End of Cycle is determined by the Boron concentration evolution
- In order to maintain the reactor "critic", the boron concentration is adjusted. When it hits a value ~ 0 ppm, the cycle ends

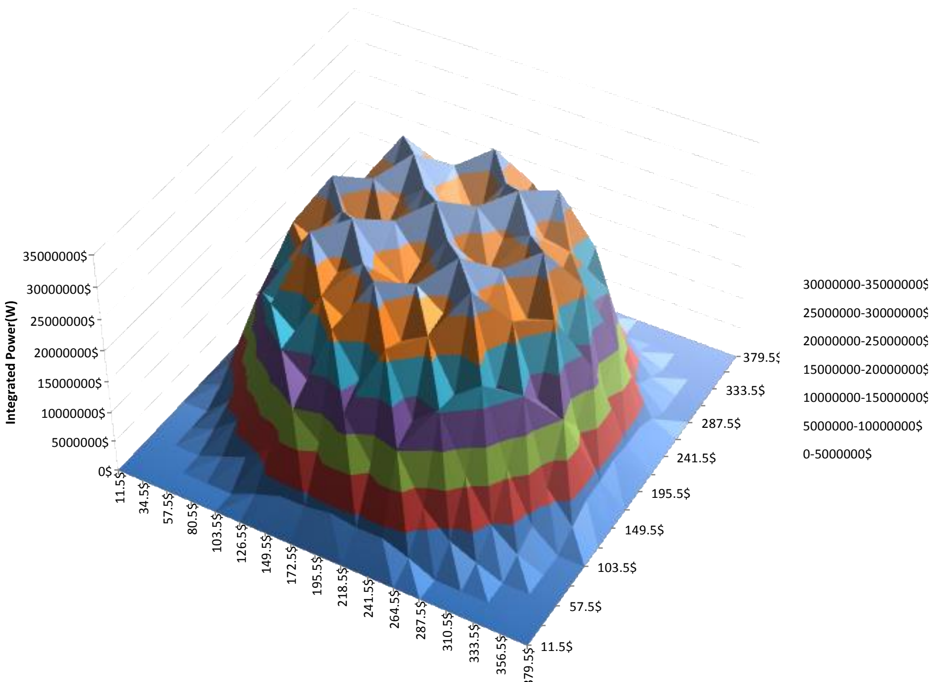


Core design Equilibrium Cycle Results

- The LOCA analysis needs to take into account the power and burnup distributions. For example, we report the Begin, Middle and End of Cycle (10th Cycle)

Begin of Cycle

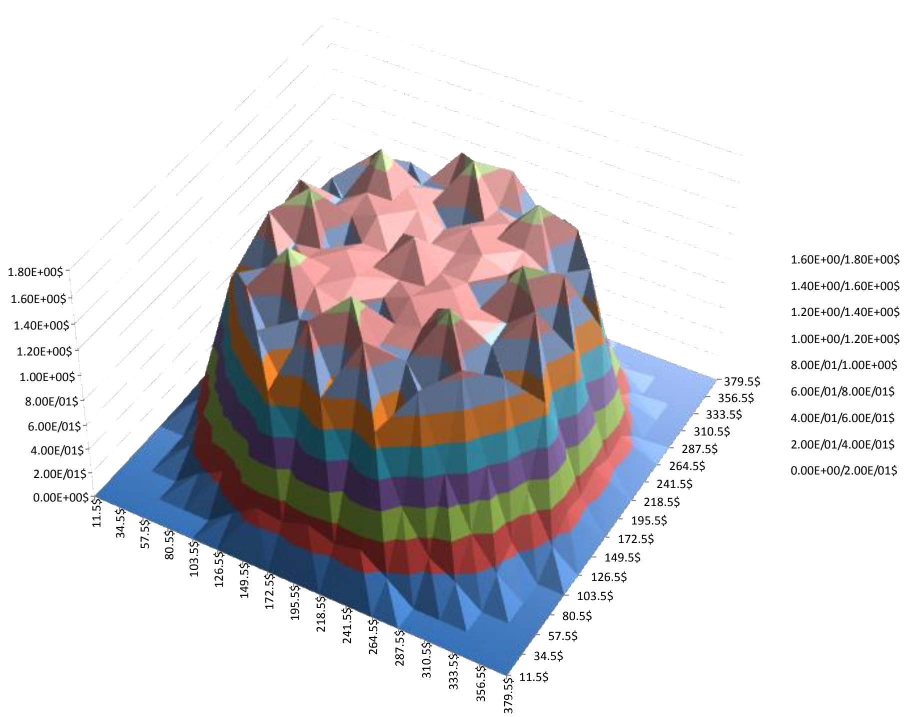


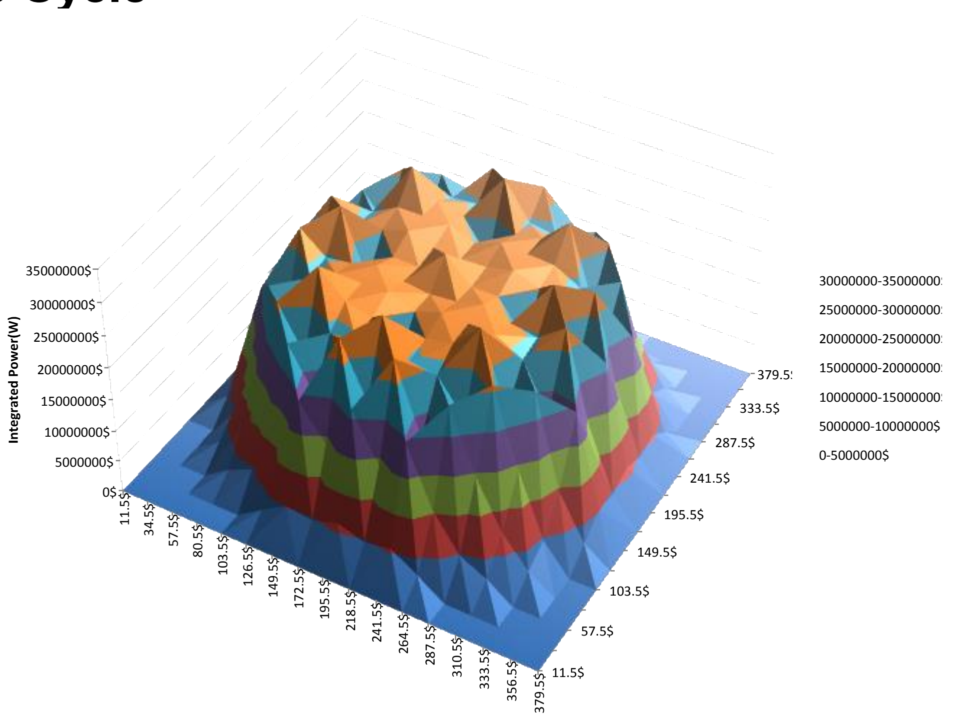


Core design Equilibrium Cycle Results

- **As expected, the radial power peaking factors start to decrease, since the depletion evolution is flatting the power distribution**

Middle Cycle

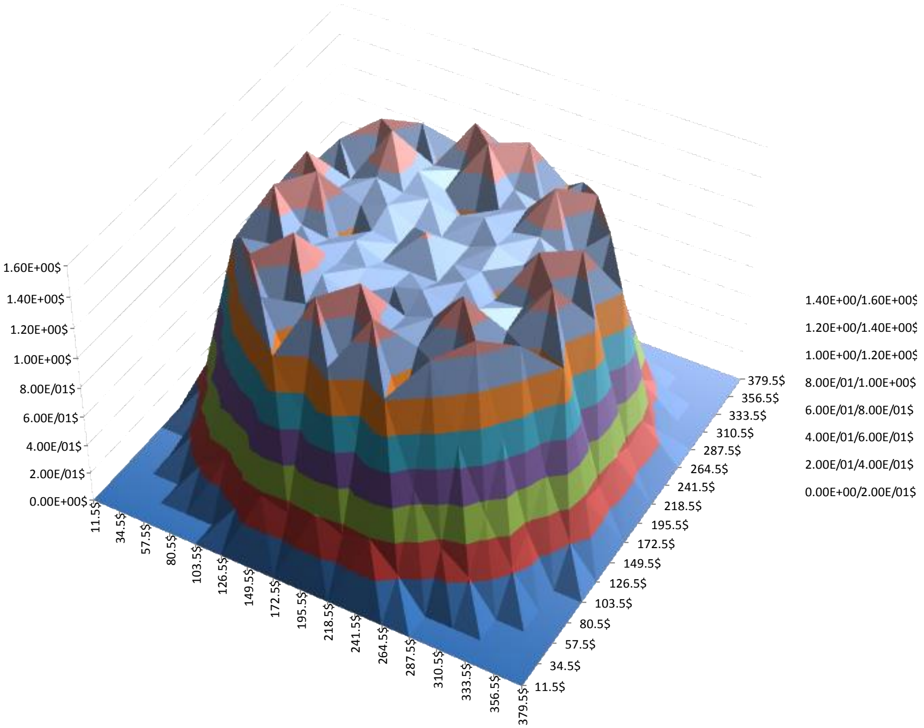


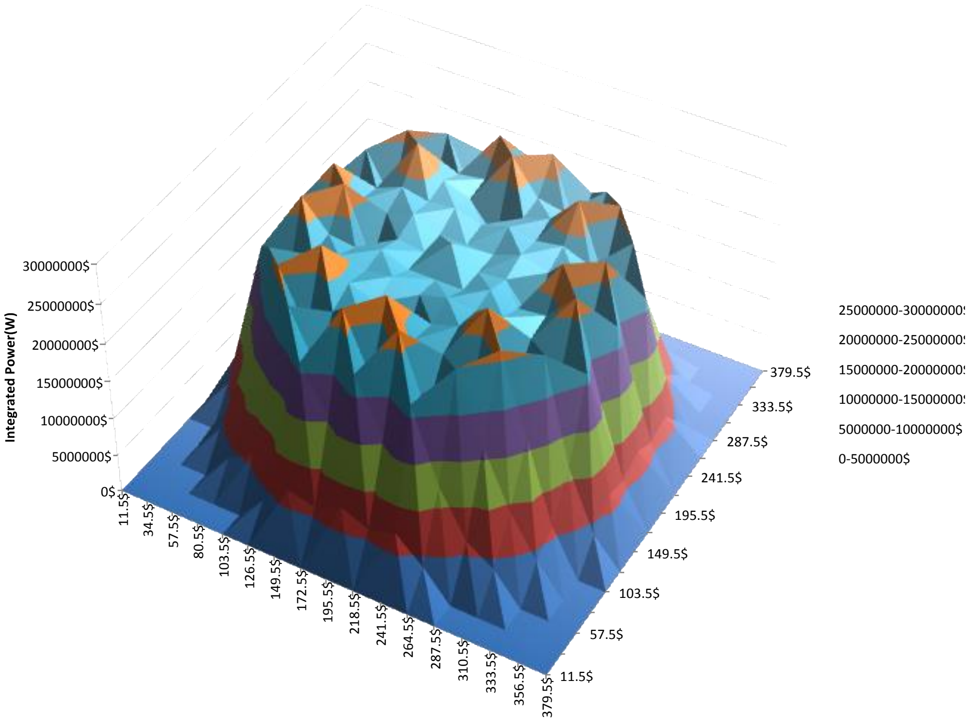


Core design Equilibrium Cycle Results

- **The power distribution is homogenous and, consequentially the radial power peaking factors are the lowest**

End of Cycle

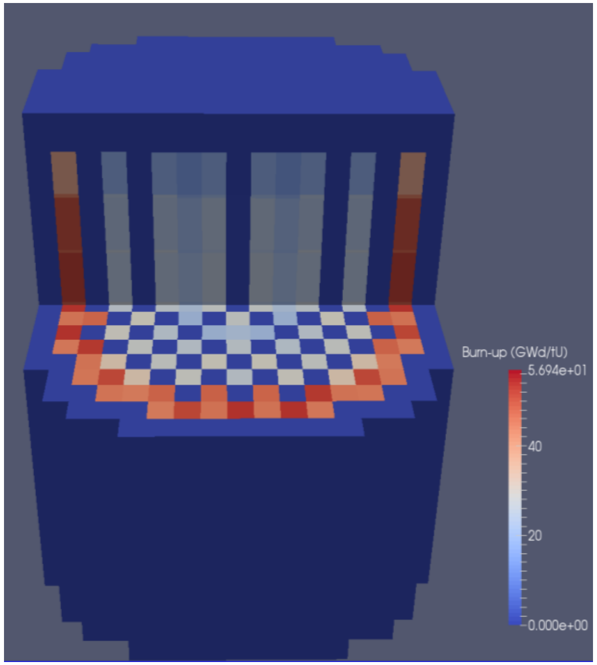




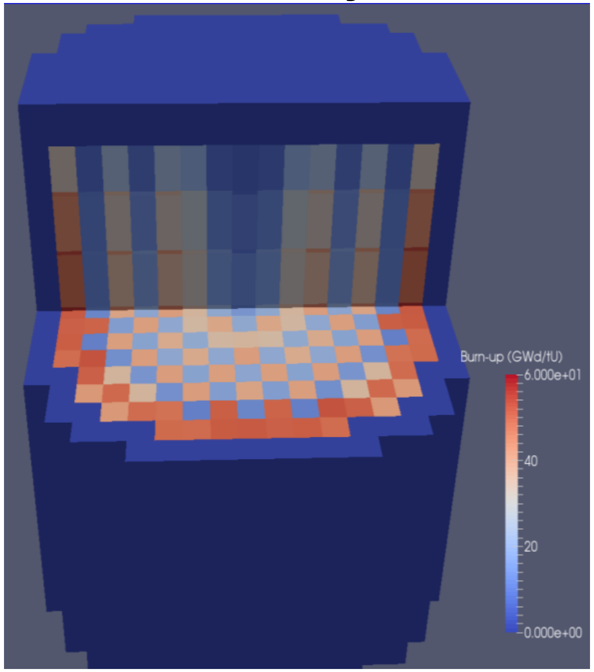
Core Design Results: Burn-Up distribution

- The new limits determine the need to take into account the Burn-up evolution of the core.

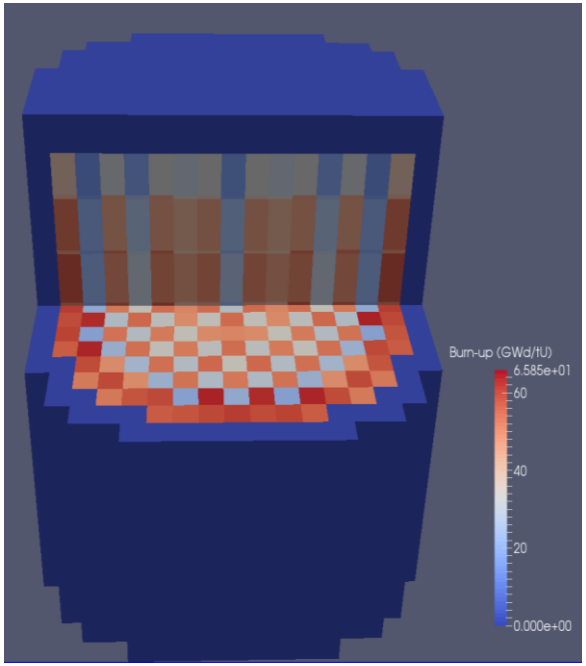
Begin of Cycle



Middle Cycle



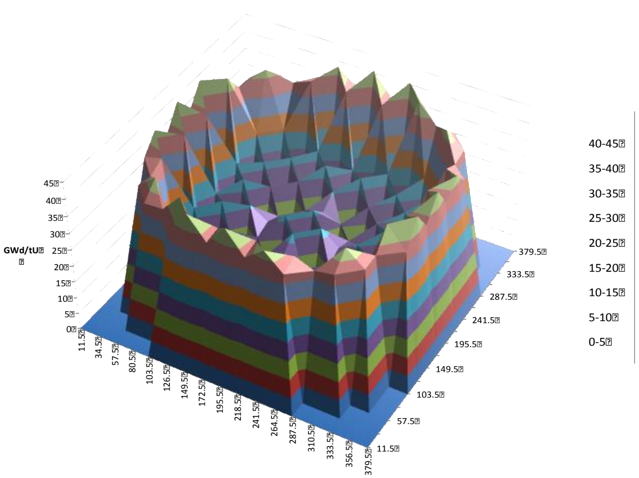
End of Cycle



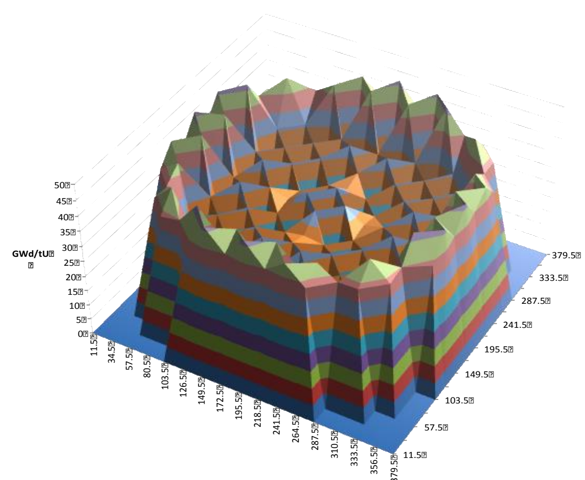
Core Design Results: Burn-Up 2D distribution

- **2-Dimensional averaged Burn-Up map**

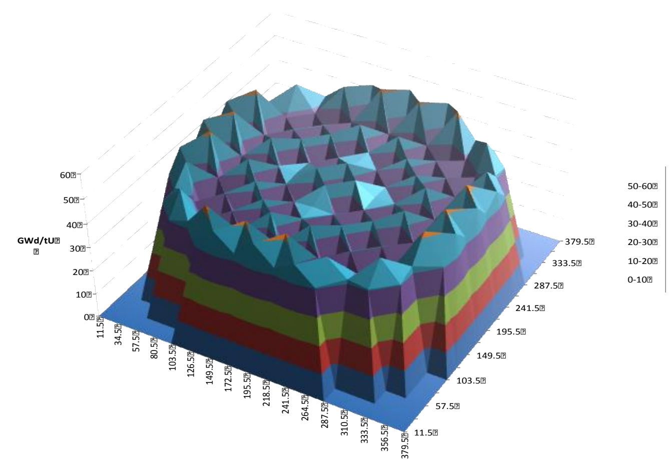
Begin of Cycle



Middle Cycle

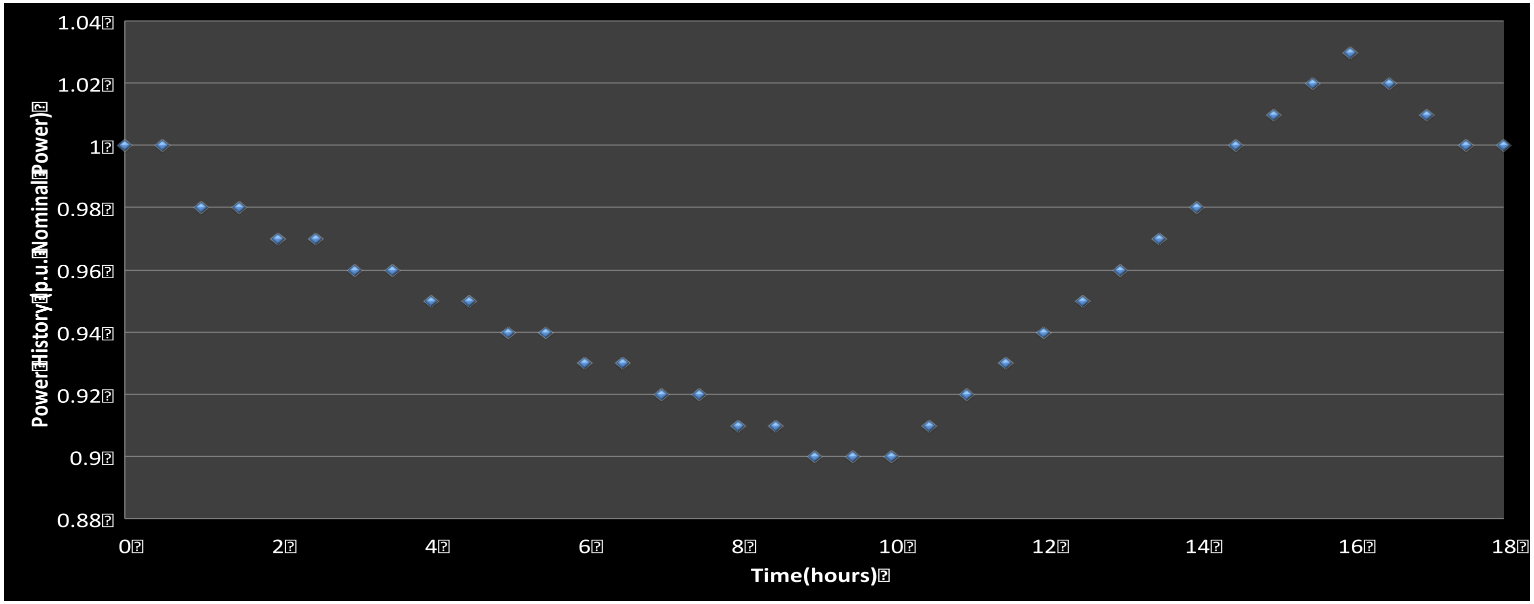


End of Cycle



Maneuver

- The core status at BOC, MOC and EOC does not determine challenging conditions for the LOCA analysis
- LOCA scenarios for the assessment of the safety margins are generally performed considering the reactor right after a maneuver that can initiate, for example, a Xenon transient.
- For the scope of this work, the maneuver that has been considered is a load-following operation of the reactor (using the Criticality search module of PHISICS)

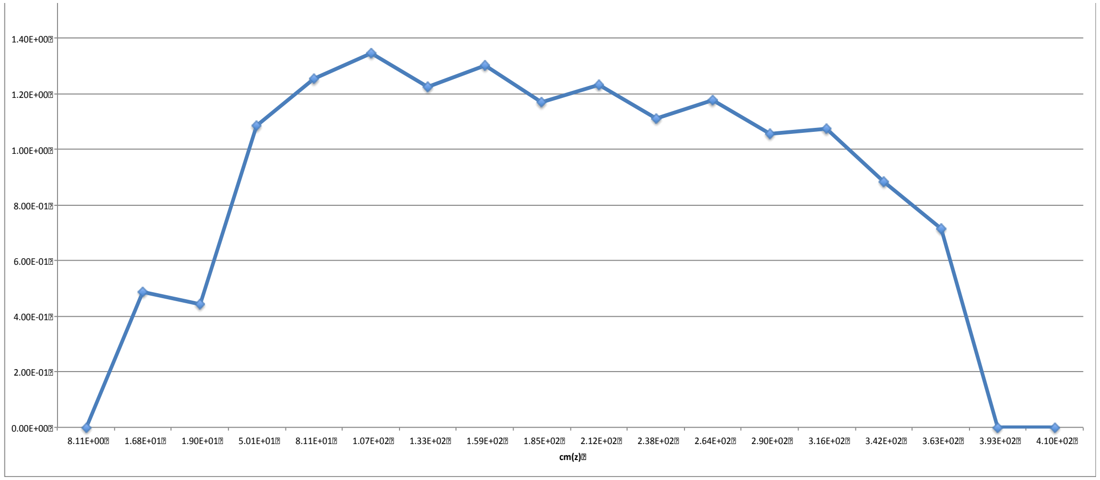


Maneuver: Results

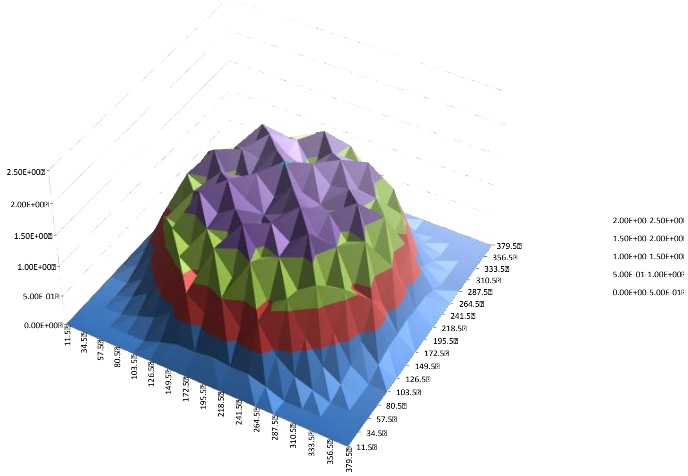
- **As an example, the end of maneuver radial and axial peaking factors are reported:**

Begin of Cycle

Axial



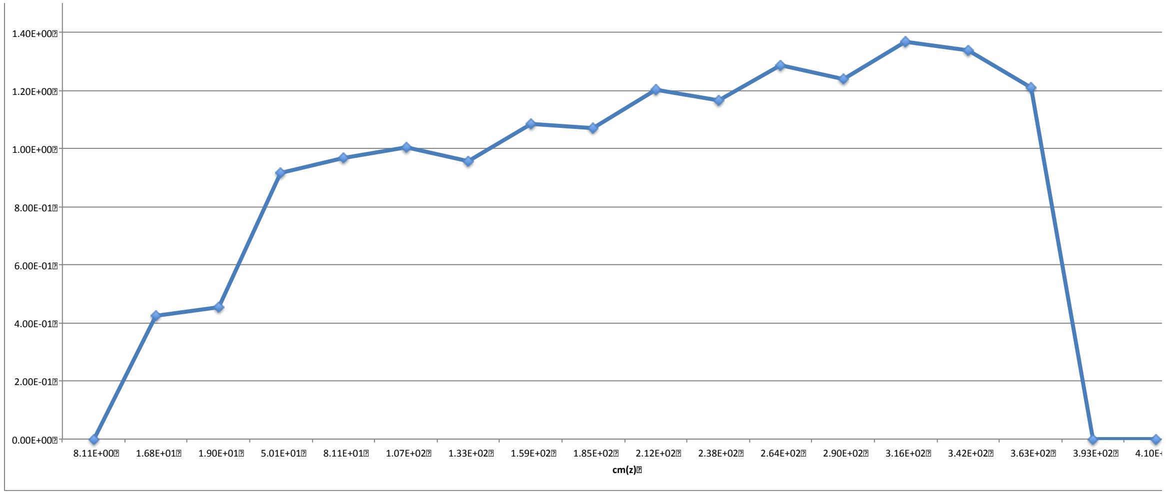
Radial



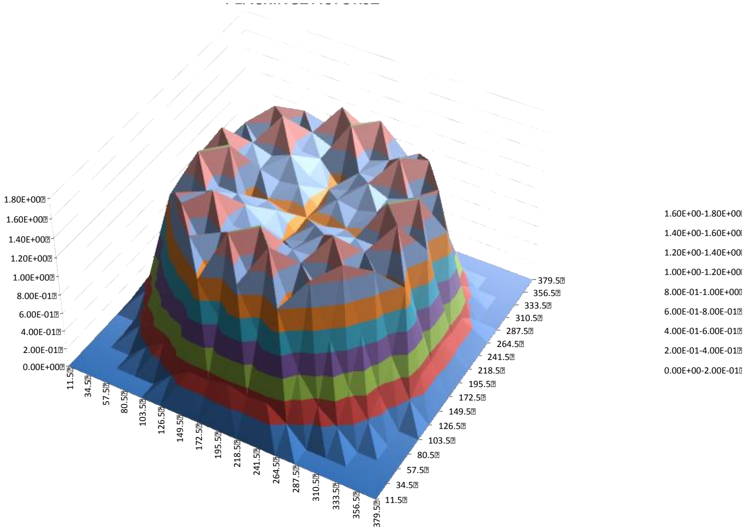
Maneuver: Results

Middle of Cycle

Axial



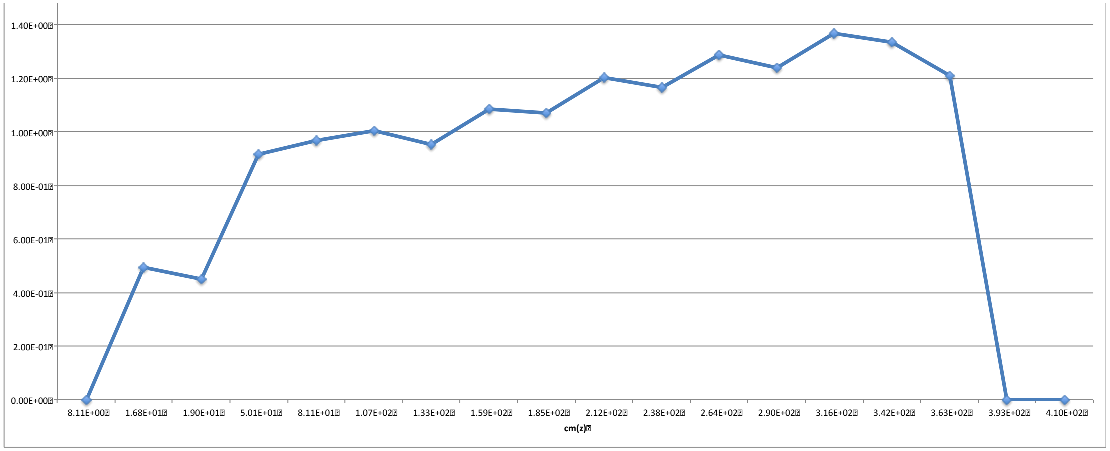
Radial



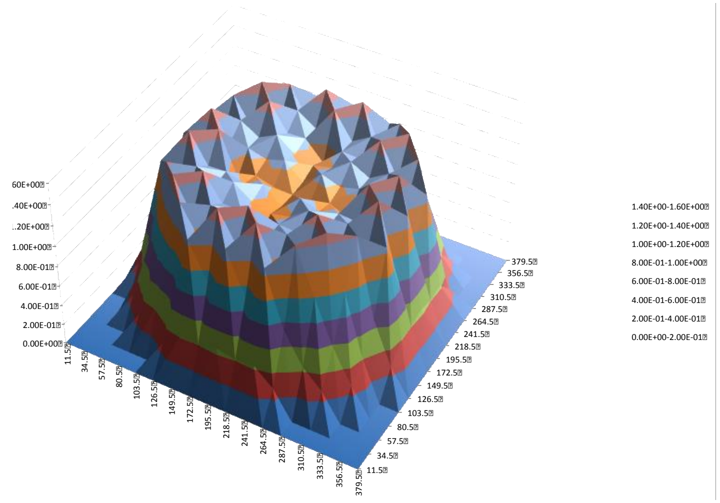
Maneuver: Results

End of Cycle

Axial

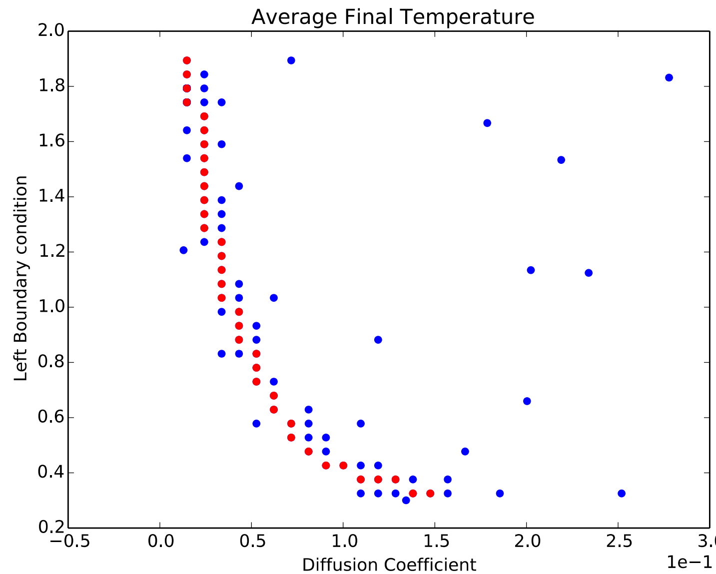


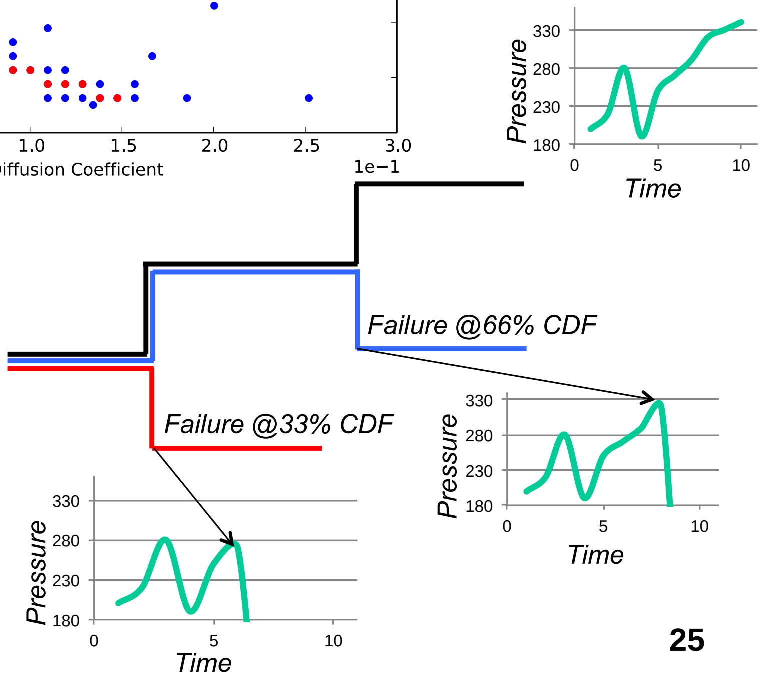
Radial



Path Forward

- **Probabilistic analysis to determine core failure probability is the next step**
- **RAVEN will be used in conjunction with PHISICS/RELAP5-3D for the probabilistic analysis:**
  - Monte Carlo
  - Dynamic Event Tree
- **Some improvement to the Dynamic Event Tree approach might be needed to reduce the computational cost**
- **Limit surface analysis will be used to highlight risk management strategies**





Summary

- **A set of capabilities of the coupled suite PHISICS-RELAP5-3D has been tested and improved.**
  - Multi-cycle/refueling
  - Criticality search for CRs
  - Usage of the multi deck capability of RELAP5-3D
- **Starting from the BEAVRS a reloading pattern has been defined to achieve:**
  - 18 month cycles
  - Average burn-up at fuel batch EOL of ~ 55 GWd/tU
  - A load following maneuver to determine peaking factors before LOCA

Helping to Sustain National Assets

LWRS

Light Water Reactor Sustainability