Overview of the RELAP5-3D code activities in ENEA

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- Recent activities using RELAP5-3D© code
  - OECD/NEA OSKARSHAMN-2 benchmark
  - AER DYN-003 benchmark
  - Gen. IV activities on Sodium Fast Reactor
- Conclusions & Future works

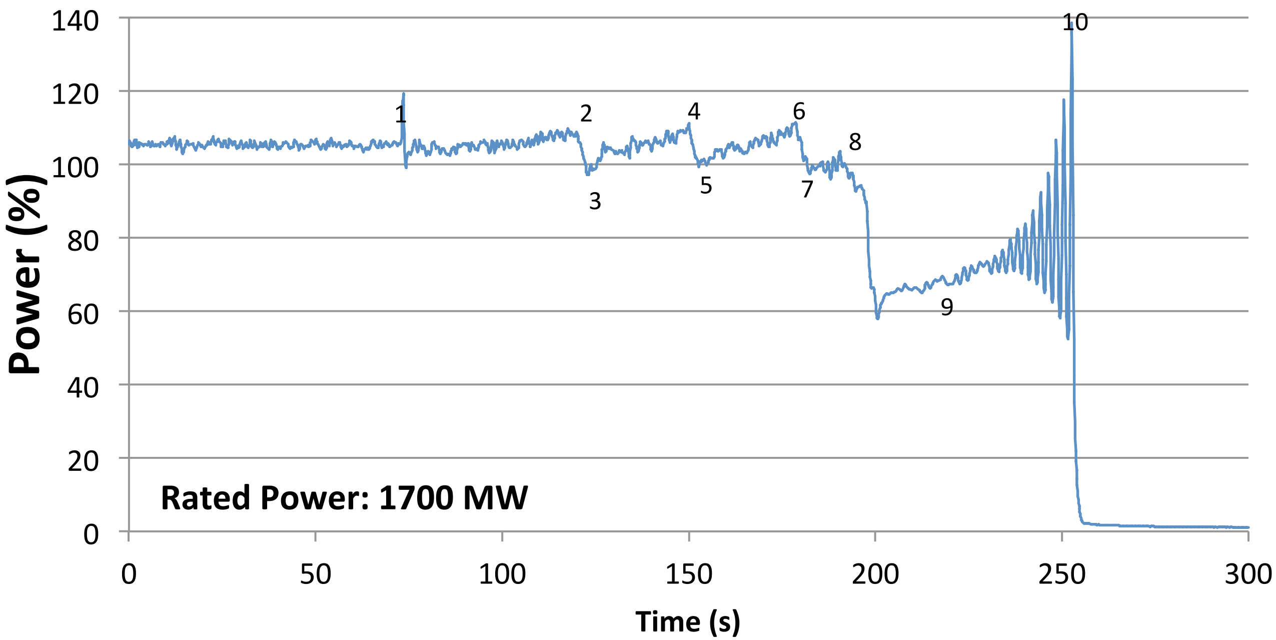
Recent activities using RELAP5-3D code

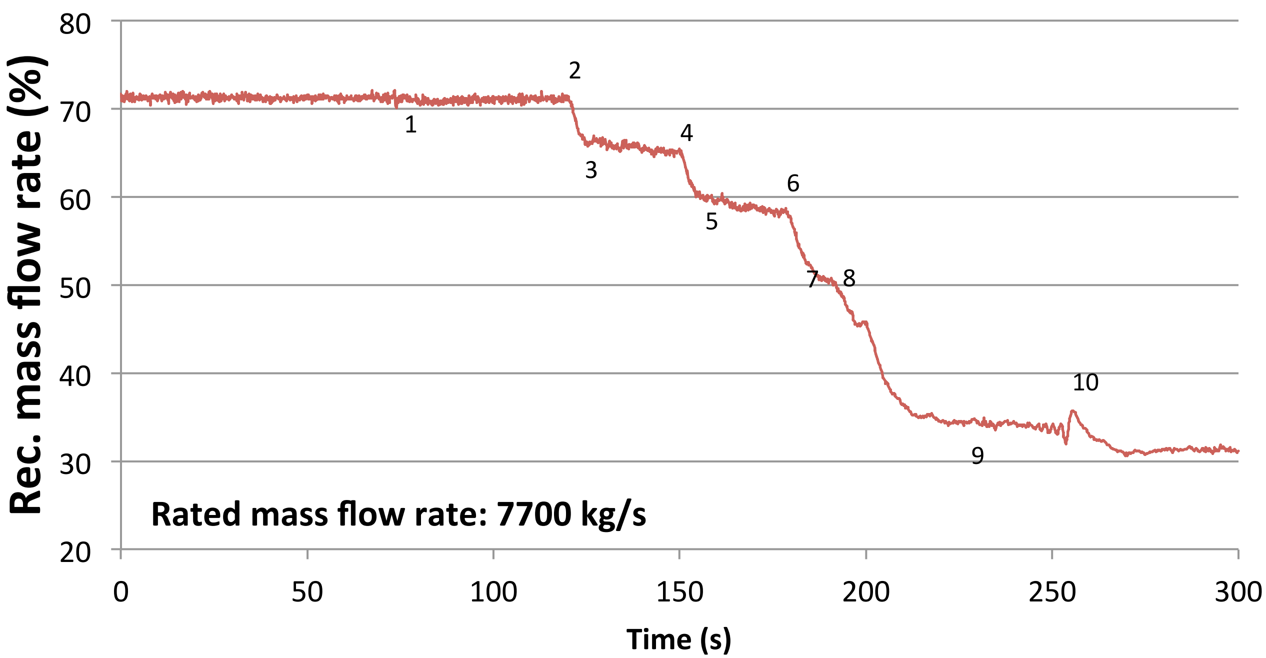
- RELAP5-3D code used for studying past, existing (Gen. II) & *future* (Gen. IV) NPP
- Participating to international code benchmarks organized by nuclear energy Institutions (OECD/NEA, AER, IAEA)
  - **"OSKARSHAMN-2": BWR global core instability event (OECD/NEA)**
  - **"DYN-003": CR Ejection in VVER-440 (AER)**
  - **"EBR-II": pump coast-down transient (IAEA)**
- **Objectives:**
  - to investigate the capabilities of codes in simulating NPP behaviors
  - to quantify codes and models uncertainties
  - to **increase** and **improve** *user experience*

O-2 benchmark

- **OSKARSHAMN-2** benchmark
  - Launched by OECD/NEA in 2011 → release 2.0 of specifications
  - Previous instability benchmarks (Forsmarsk and Ringhals) characterized by decay ratio<1.0 & based on noise measurement of a stable reactor
  - **O-2** 1999 event is an instability event with a DR>1 (diverging oscillation)
  - Challenging simulation for a coupled code
    - Detalied RPV/core nodalization needed
    - Core parameters changing on a great magnitude
      - Core power going from 100% to 60%, then up to 130%
    - Tightly coupled NK-TH transient

The 1999/02/25 event





Event Description	
1	Turbine trip and bypass valves opening
2	First 108% power level exceeding
3	Stop Reducing pump velocity
4	Second 108% power level exceeding
5	Stop Reducing pump velocity
6	Third 108% power level exceeding
7	Stop Reducing pump velocity
8	Operator Partially scrammed the reactor and reduced to the minimum the pump velocity.
9	Reactor enter in the unstable region of the power/flow map
10	The reactor scrammed because the power exceeded 132 %

Code Used

- RELAP5-3D© used for the Oskarshamn-2 benchmark

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  - TH phenomena (1D & 3D components)
  - internal r

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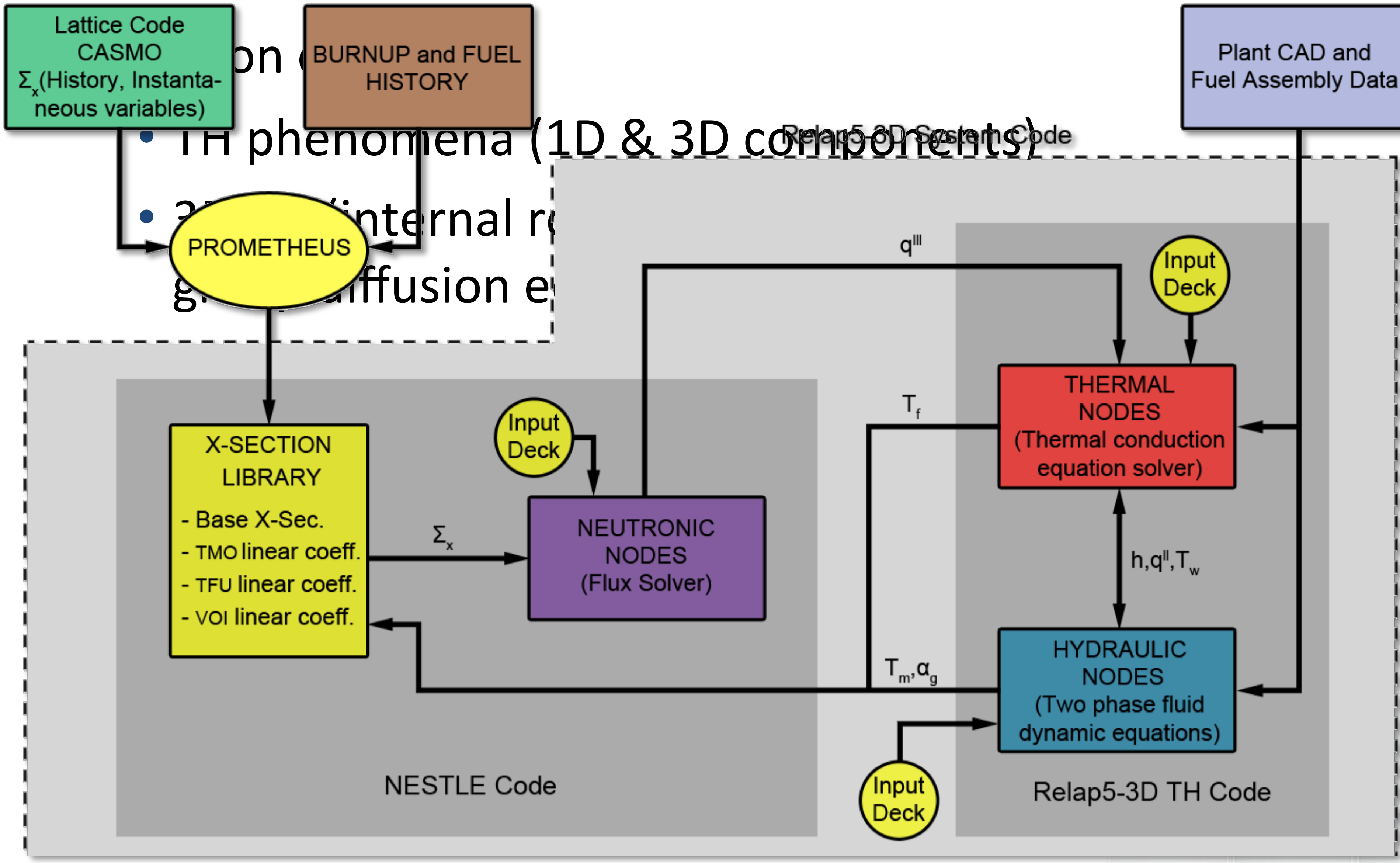
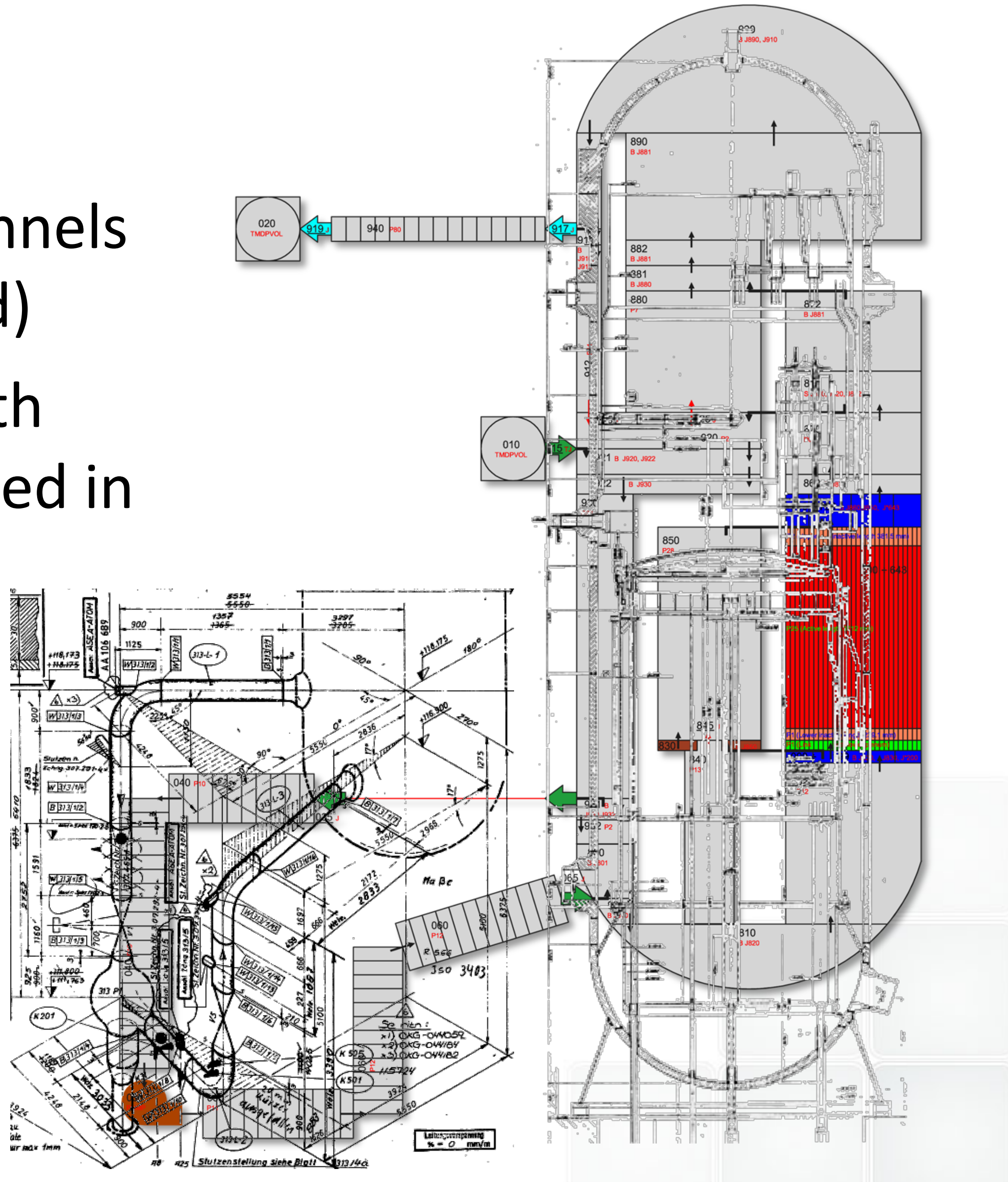


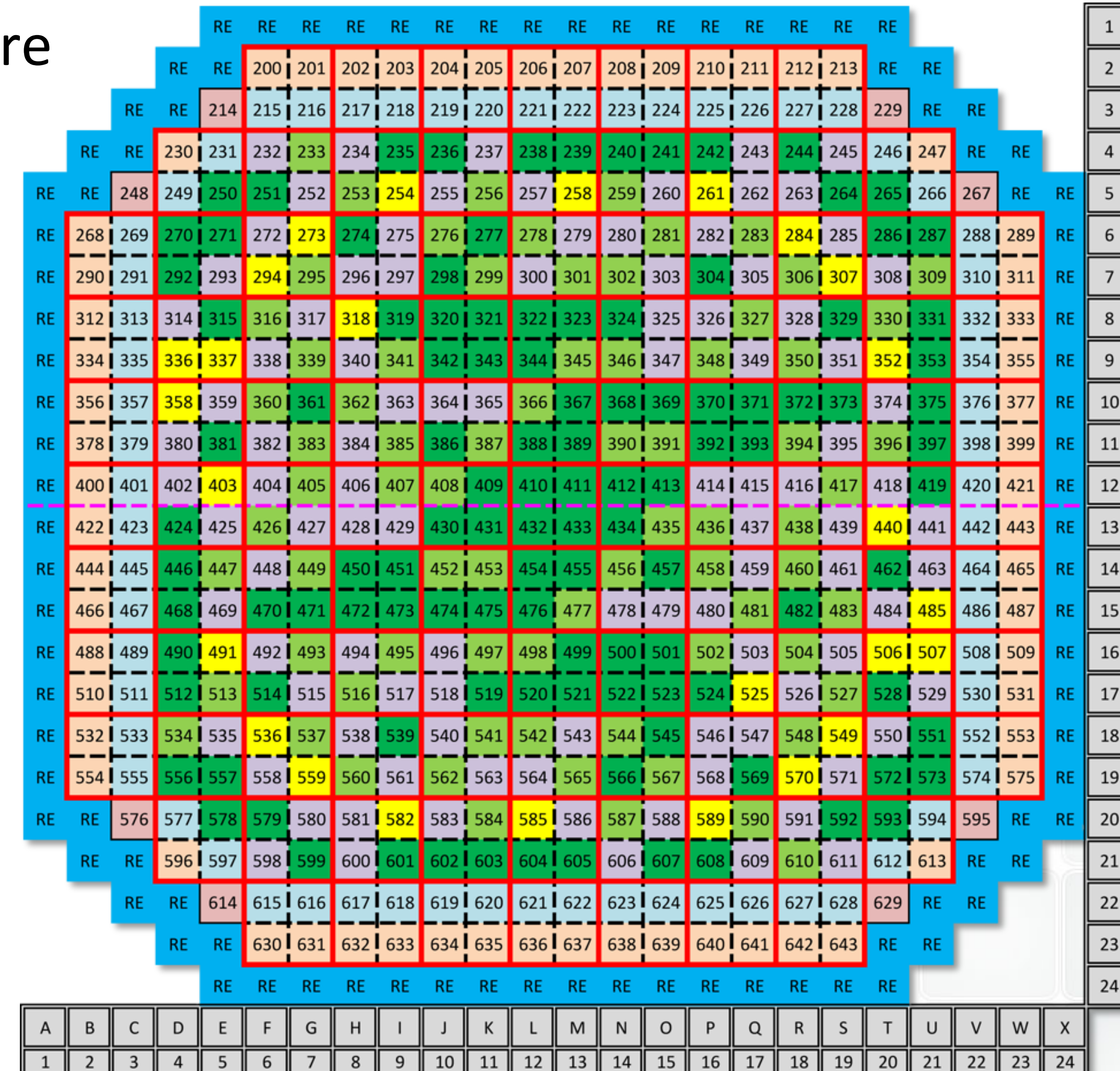
Reactor Coolant System modelling

- RCS TH nodalization
  - Number of Hydraulic volumes: **489** (core channels and bypass not included)
  - **4** recirculation loops with external pumps (collapsed in one)
  - **4** steam lines (collapsed in one)
  - Passive Heat structures still not simulated



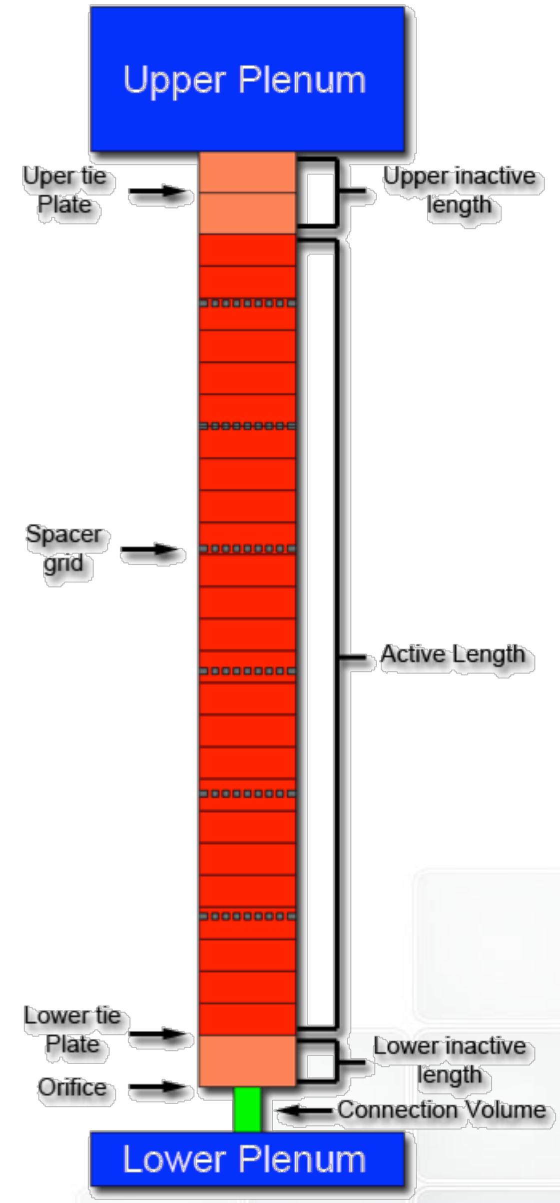
Core modelling

- **444** Channels core nodalization



Core TH & NK nodalization

- Base model: Core Axial meshing:
  - Uniform meshing for the active part **25** Hydraulic mesh + **25** Thermal mesh + **25** Neutronic mesh
  - **3** Hydraulic mesh + **2** Neutronic mesh for the bottom & top reflector
  - **1** Hydraulic meshes for FA inlet zone
- Core statistics
  - **444** independent TH channels +**1** (Bypass)
  - **12876** Hydraulic volumes+ **29** (Bypass)
  - **14472** NK nodes (including Reflector)

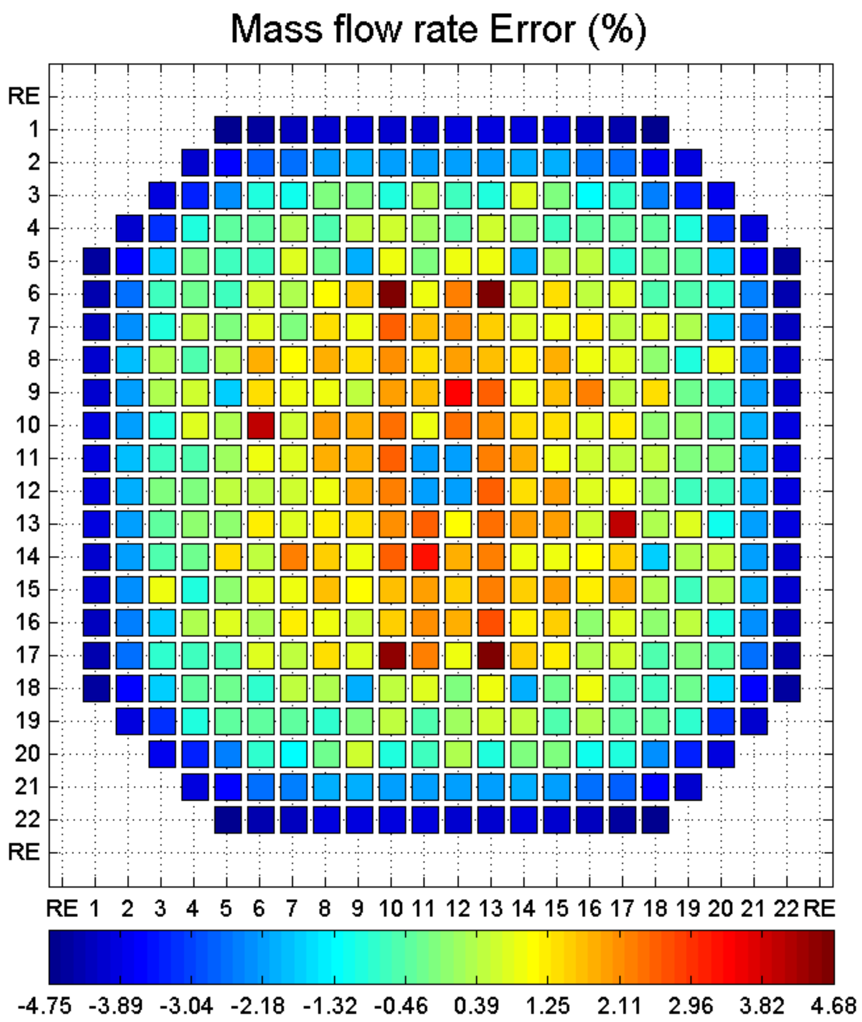


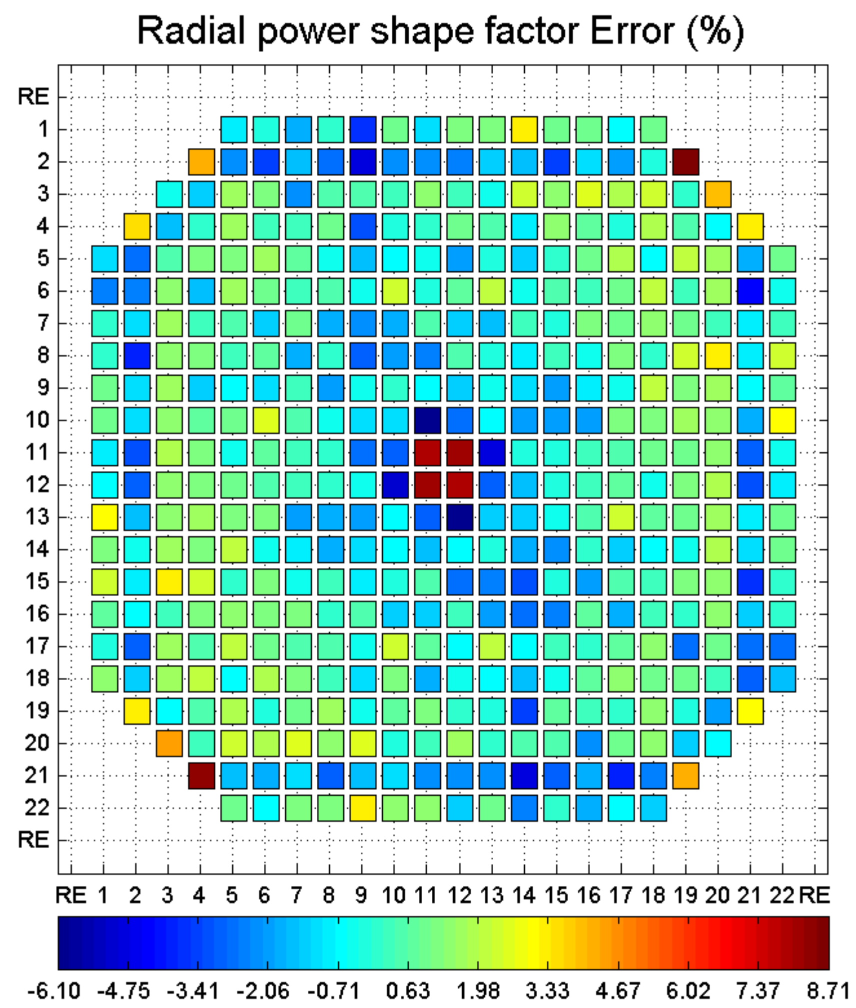
Steady state analysis results

NAME	u.d.m	NPP	NPP Code	RELAP5-3D	Rel. error
Reactor Power	MW	1798.6	1802	1798.6	IMPOSED
Steam Dome Pressure	MPa	6.93	7.00	6.93	0.00%
Core Inlet Pressure	MPa	N/A	7.166	7.087	-1.11%
Core Outlet Pressure	MPa	N/A	7.067	6.988	-1.12%
Core ΔP	kPa	N/A	98.8	98.6	-0.23%
Channel ΔP	kPa	N/A	46.0	48.2	4.72%
Orifice & Lwr plate ΔP	kPa	N/A	52.8	50.4	-4.54%
Core Average Void	//	N/A	0.42	0.44	3.79%
Core Average Fuel Temp	K	N/A	816.7	813.08	-0.44%
Feed water Temperature	K	457.6	N/A	457.6	IMPOSED
Core Inlet Temperature	K	547.30	548.05	546.99	-0.06%
Steam Temperature	K	N/A	N/A	557.83	N/A
Pump Speed	Rad/s	N/A	N/A	99.45	N/A
Total Core Flow Rate	kg/s	5474.0	5515.9	5474.0	0.00%
Active Core Flow Rate	kg/s	N/A	4793.5	4757.1	-0.76%
Steam Flow Rate	kg/s	900.0	976.0	903.8	0.42%
Downcomer Water Level	m	N/A	N/A	8.4	N/A
K-eff	//	N/A	1.0026	1.0031	50 pcm

Steady state analysis results

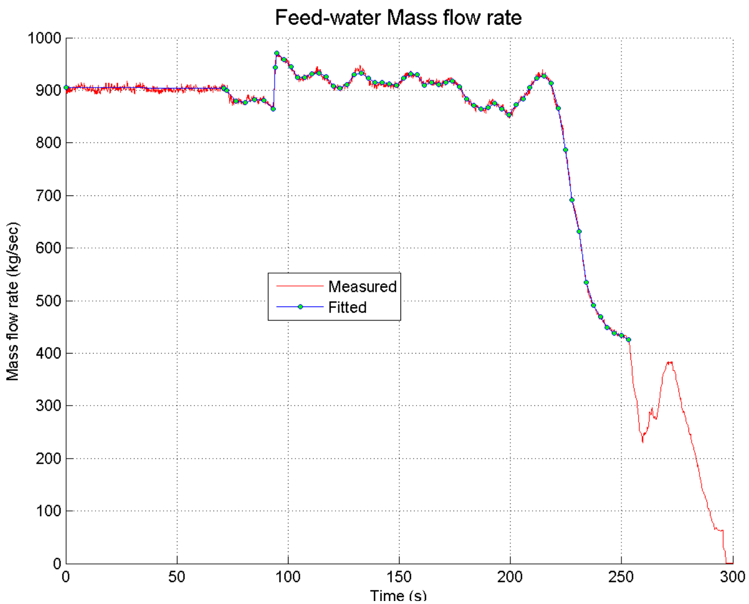
- Power Radial shape factor mass flow errors for all 444 FA

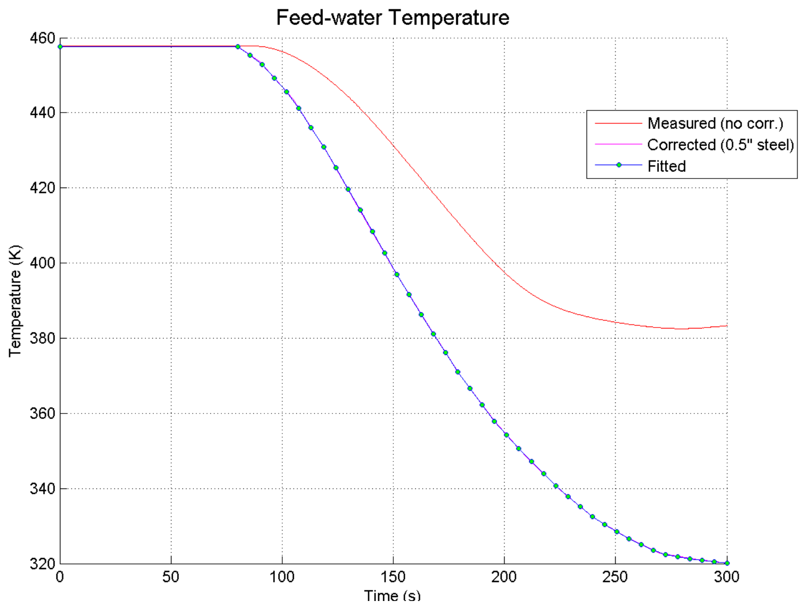


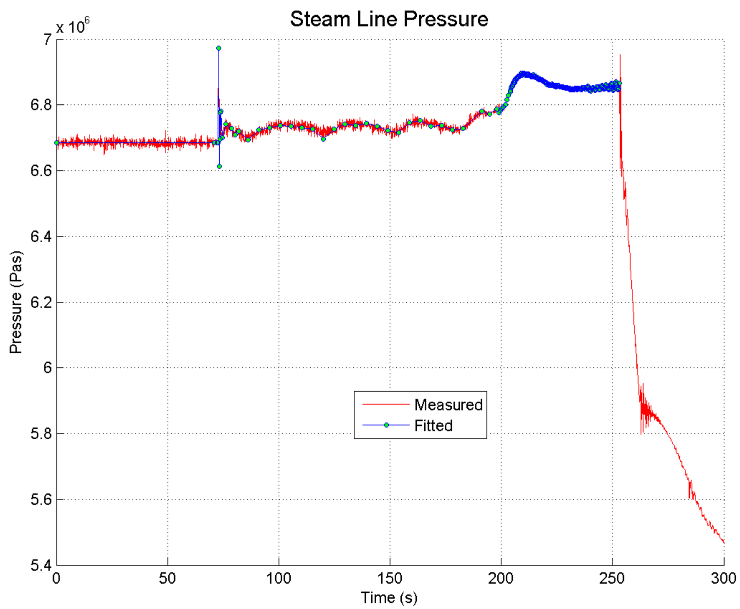


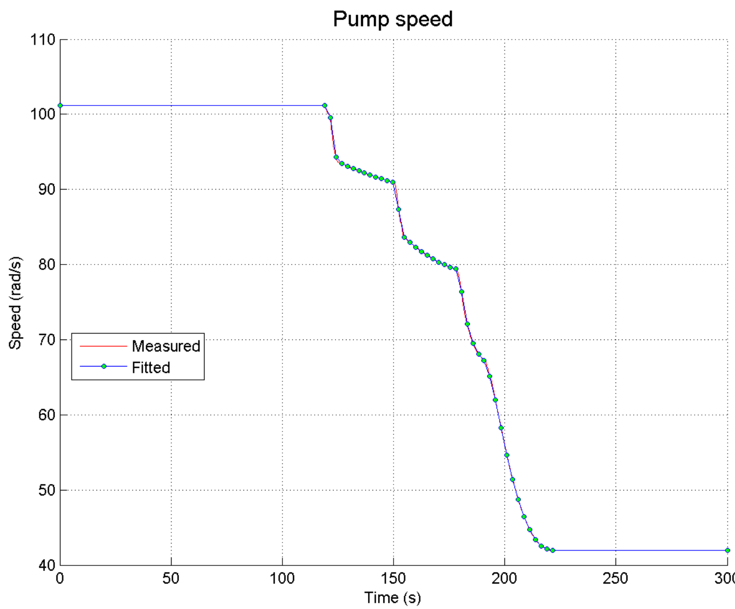
Transient analysis results

- Boundary conditions



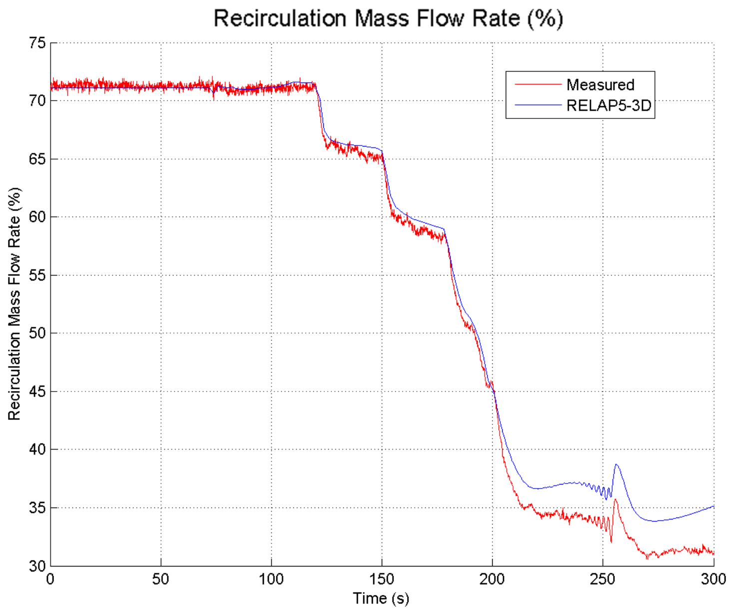


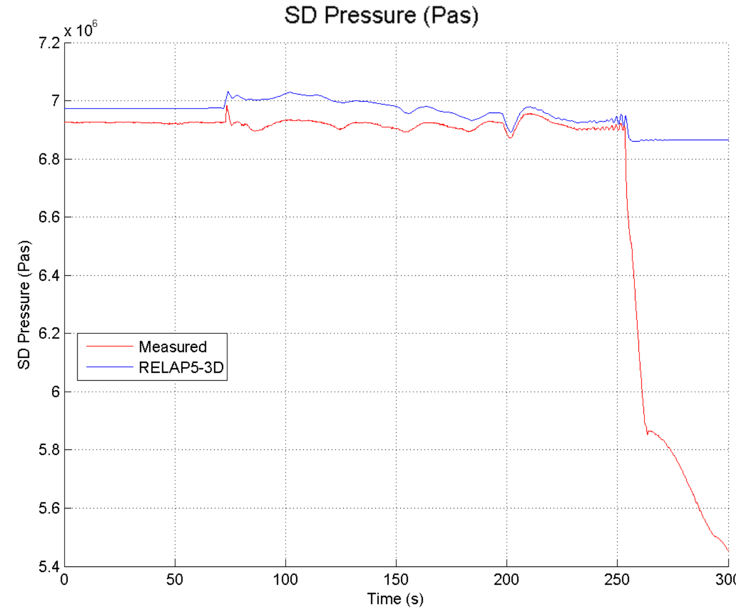


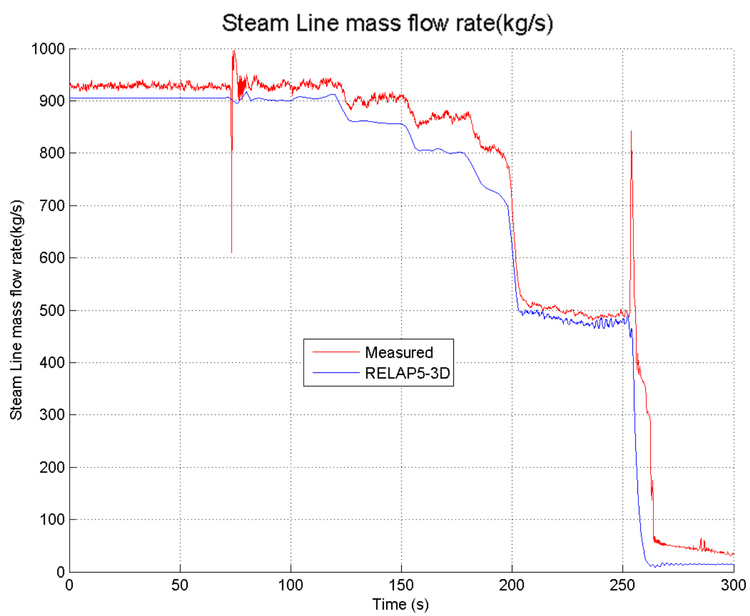


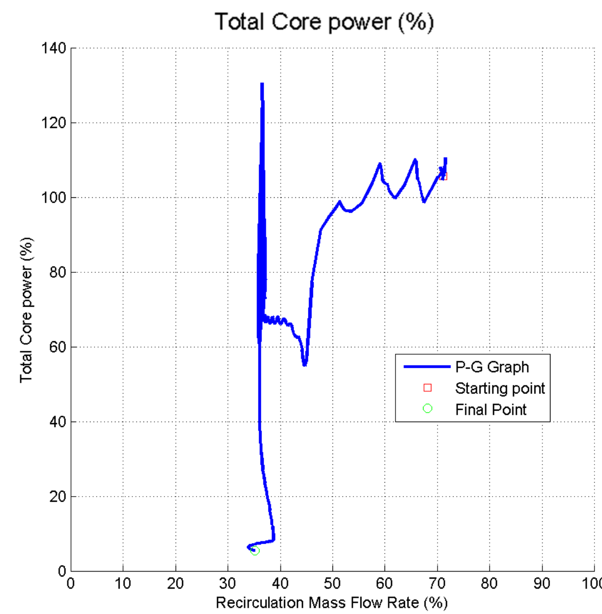
Transient analysis results

- Recirculation MFR, SD Pressure, SL MFR, Power Flow map



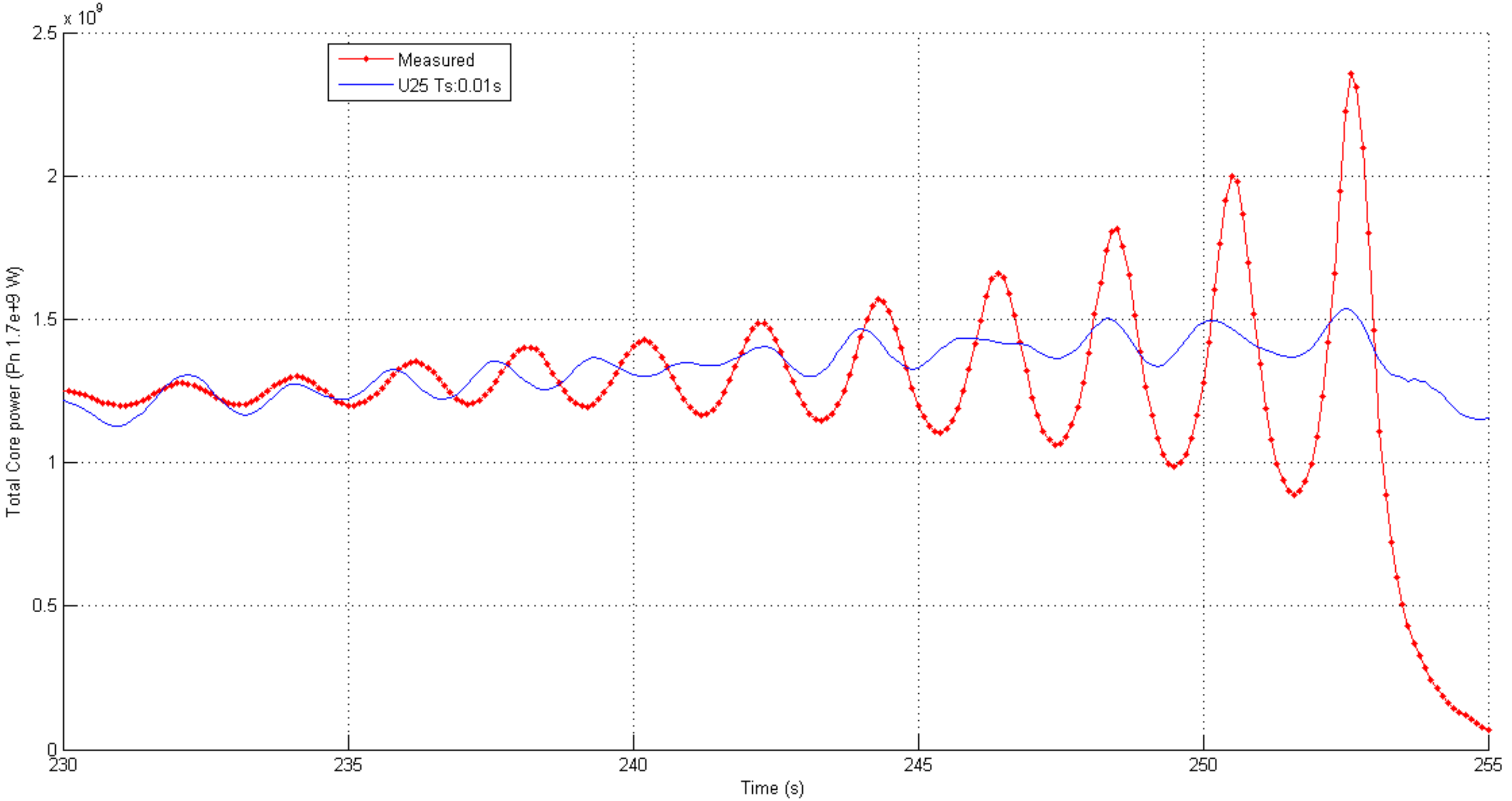






Transient analysis results

- **Homogeneous axial meshing model** → damped oscillations

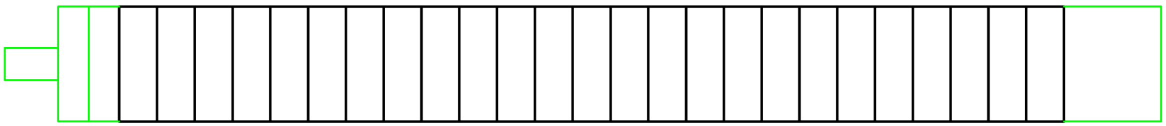


Transient analysis results

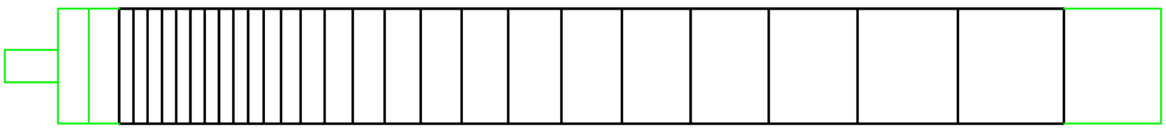
- Possible causes:
  - **Numerical diffusion**, which has a strong dampening effect using *first-order discretization* methods
  - Not well-defined **boiling height**, caused by too large mesh at the bottom of the core
- Solution:
  - Use an **heterogeneous axial mesh**, proportional to the velocity of the dominant phase, to obtain a Courant number in each mesh as close as possible to the unity (minimize numerical diffusion)
  - **Increase the number of mesh**, improving the refinement → problem: **limitation from the maximum available number of zones** → switch from the original 444 TH channel model to a 222 TH channel model (use half core symmetry)

Transient analysis results

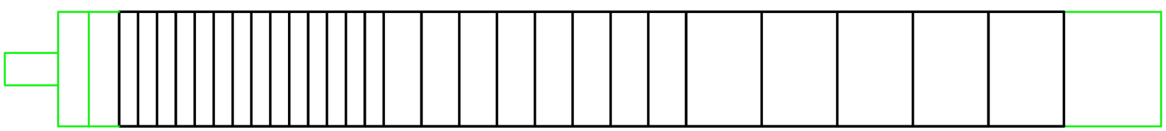
- Currently testing 4 different models



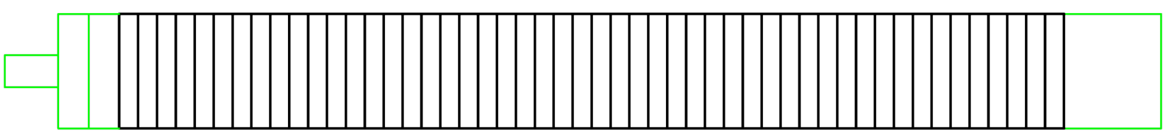
U25: 25 identical mesh
Max time step: 0.01s



NU25: 25 mesh to optimize the Courant number
Max time step: 0.03s



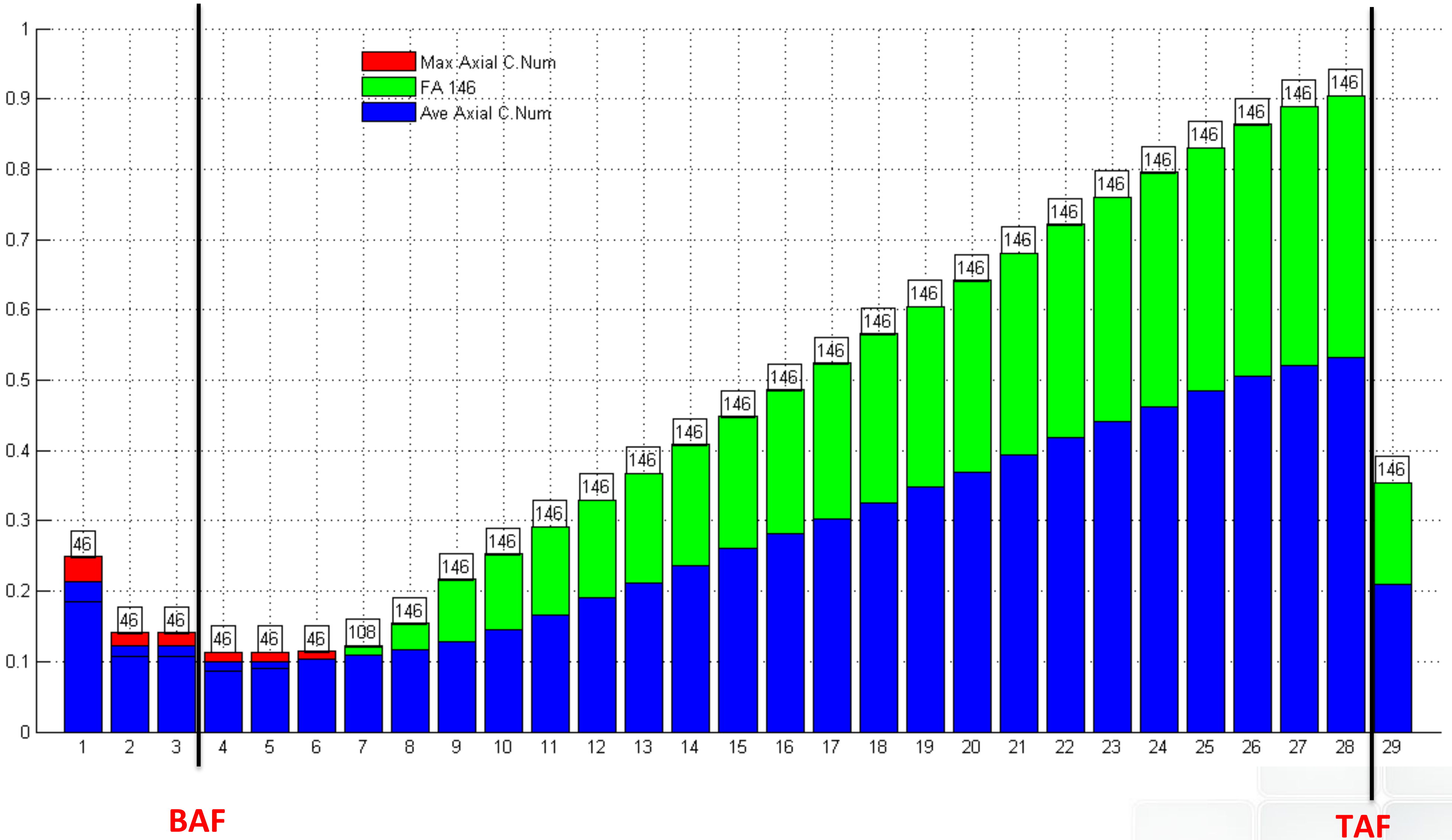
G7: the first 7 halved and the last five doubled
Max time step: 0.015s



U50: 50 identical mesh
Max time step: 0.005 s

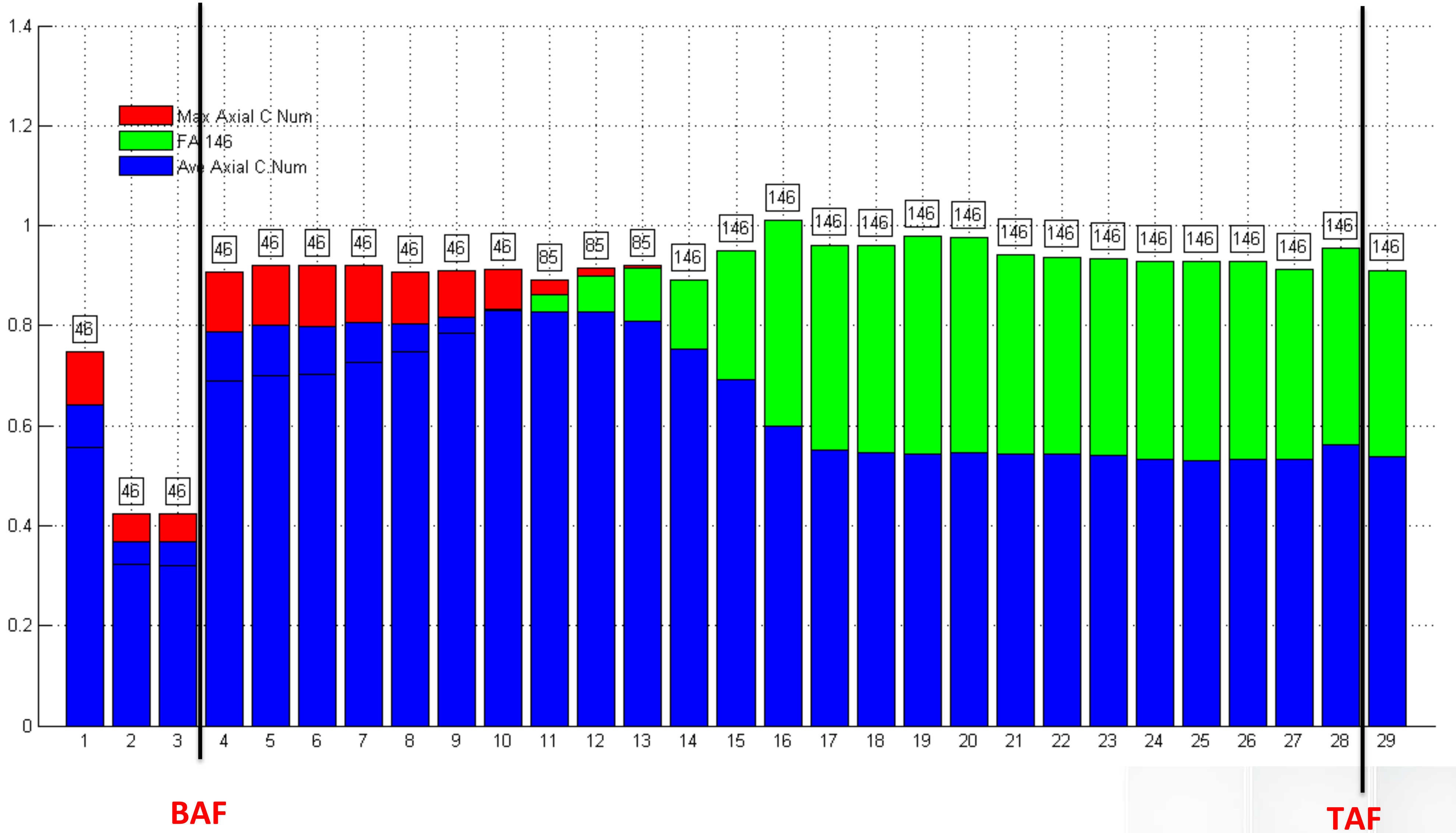
Transient analysis results

- Max and Average Core Courant number Axial profile



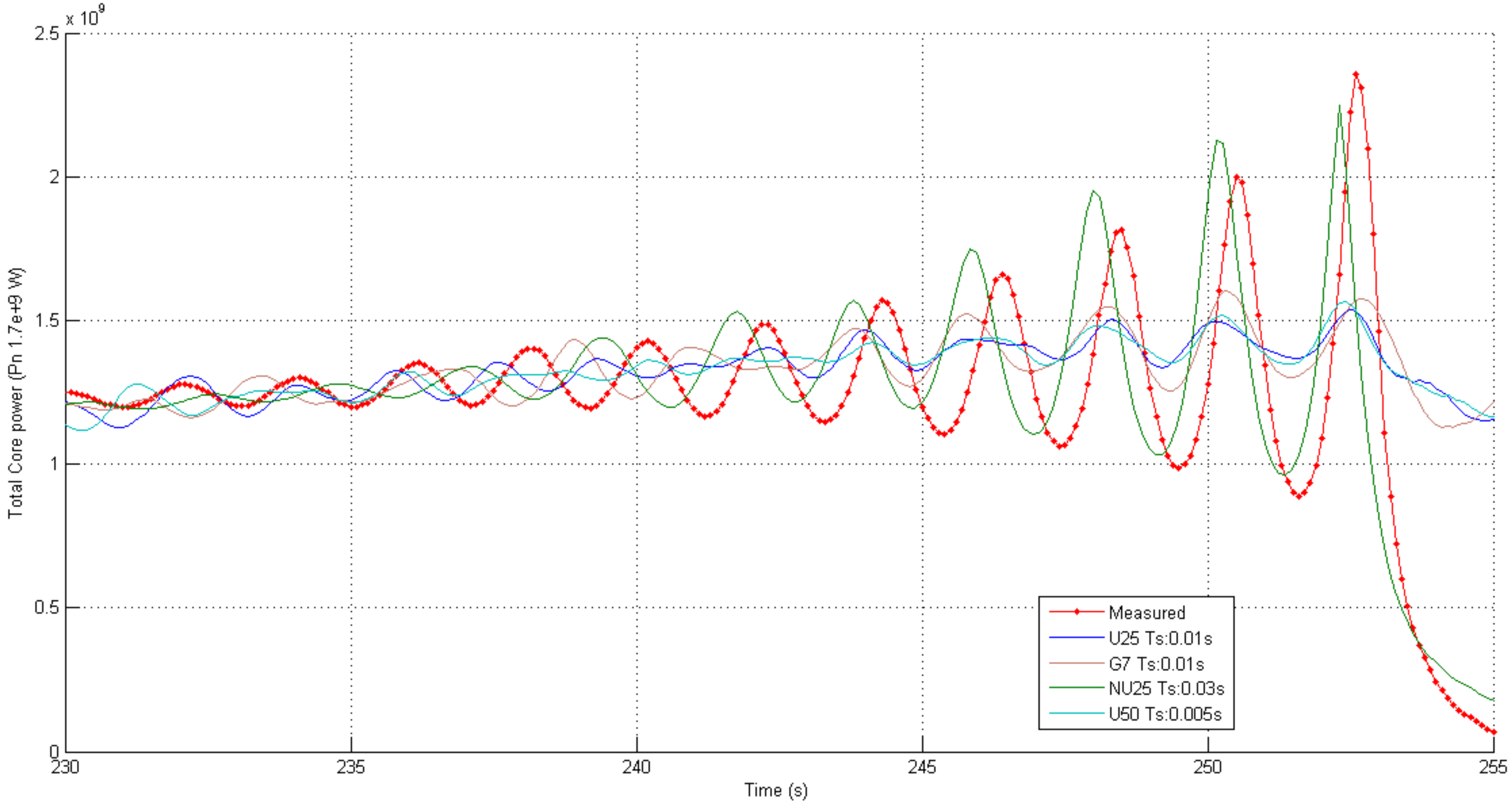
Transient analysis results

- New Max and Average Core Courant number of the **NU25** model



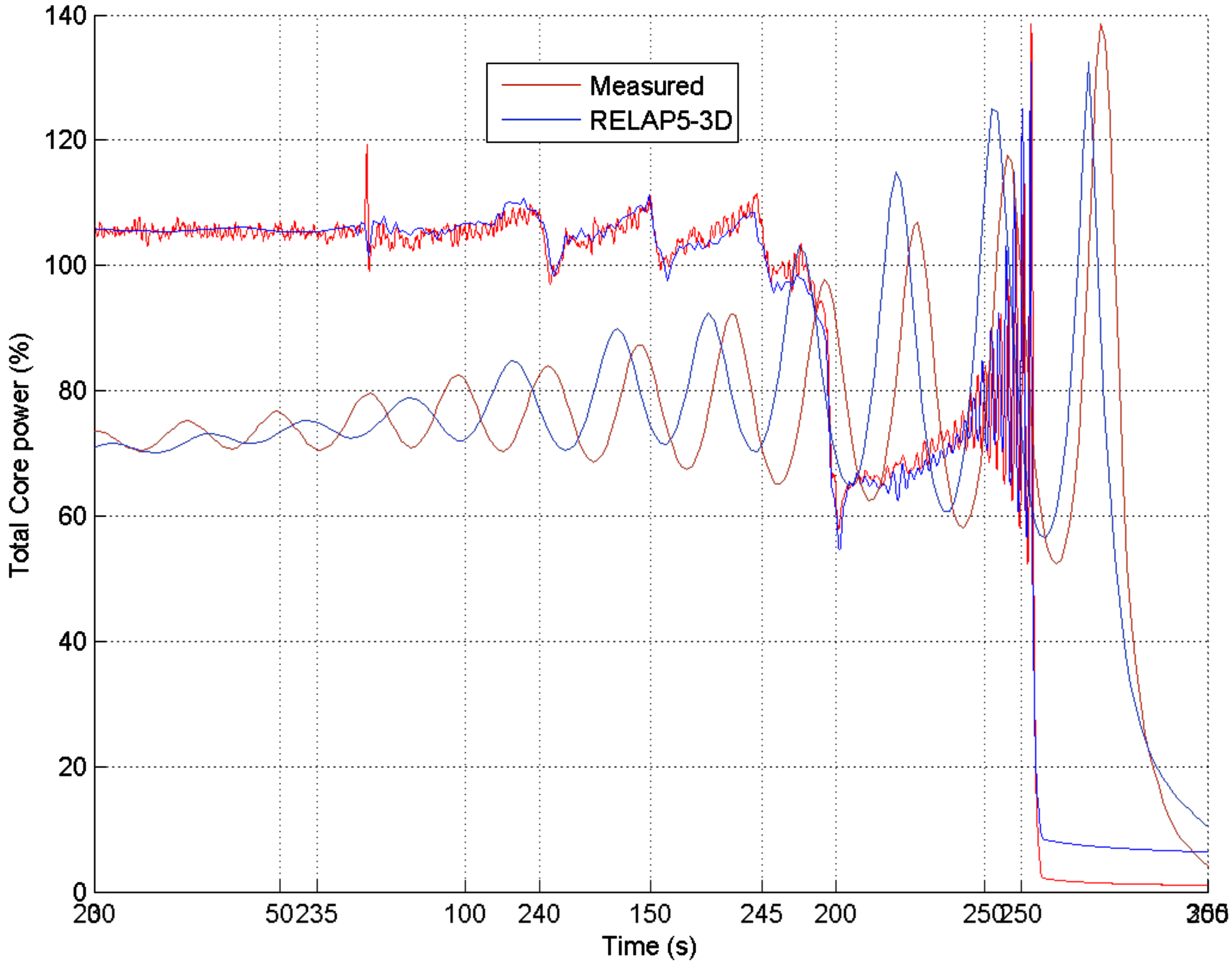
Transient analysis results

- Oscillations using The Different Models



Transient analysis results

- Total core Power (**NU25** Ts=0.03 s)

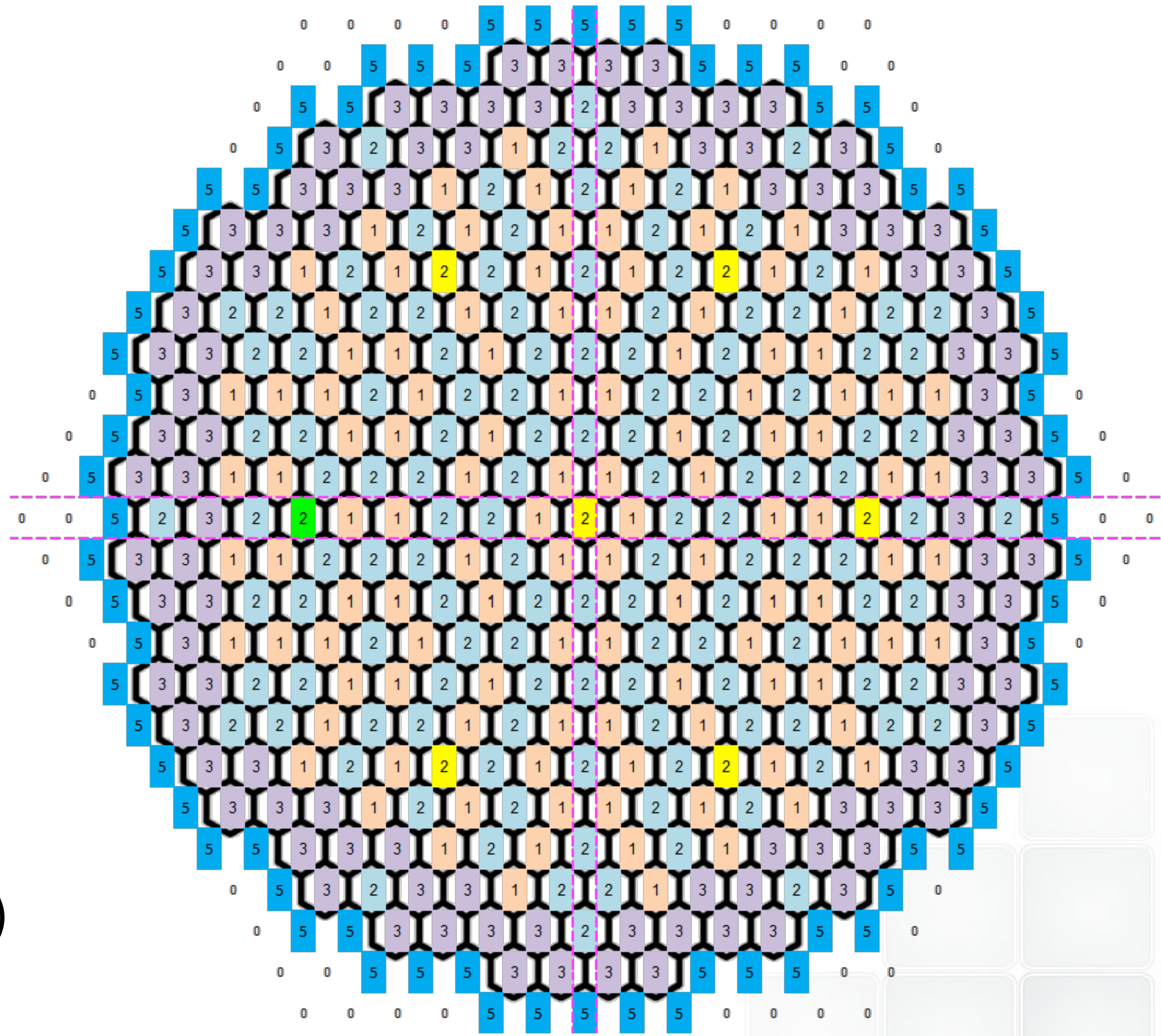


Conclusions on O2 & Future works

- Core Axial Meshing transient solution **influence** identified → **finding the converged solution** by performing **sensitivities** on **axial meshes/ time steps**
- **Limitation** on TH mapping did not allow to connect 1:1 the TH volumes & NK nodes (9999 zone figures available vs., e.g. 444x25=11100 requested) → "homogenization" or reduce TH channels
- Future further steps for the model qualification:
  - Use NESTLE compatible X-Section library using **NEMTAB** data format (being released in these weeks)
  - Use the new INL-developed neutronic package, **PHISICS,** to take advantage of the features introduced in this new code and overcome some NESTLE limitations (e.g., XSec on-line interpolation)

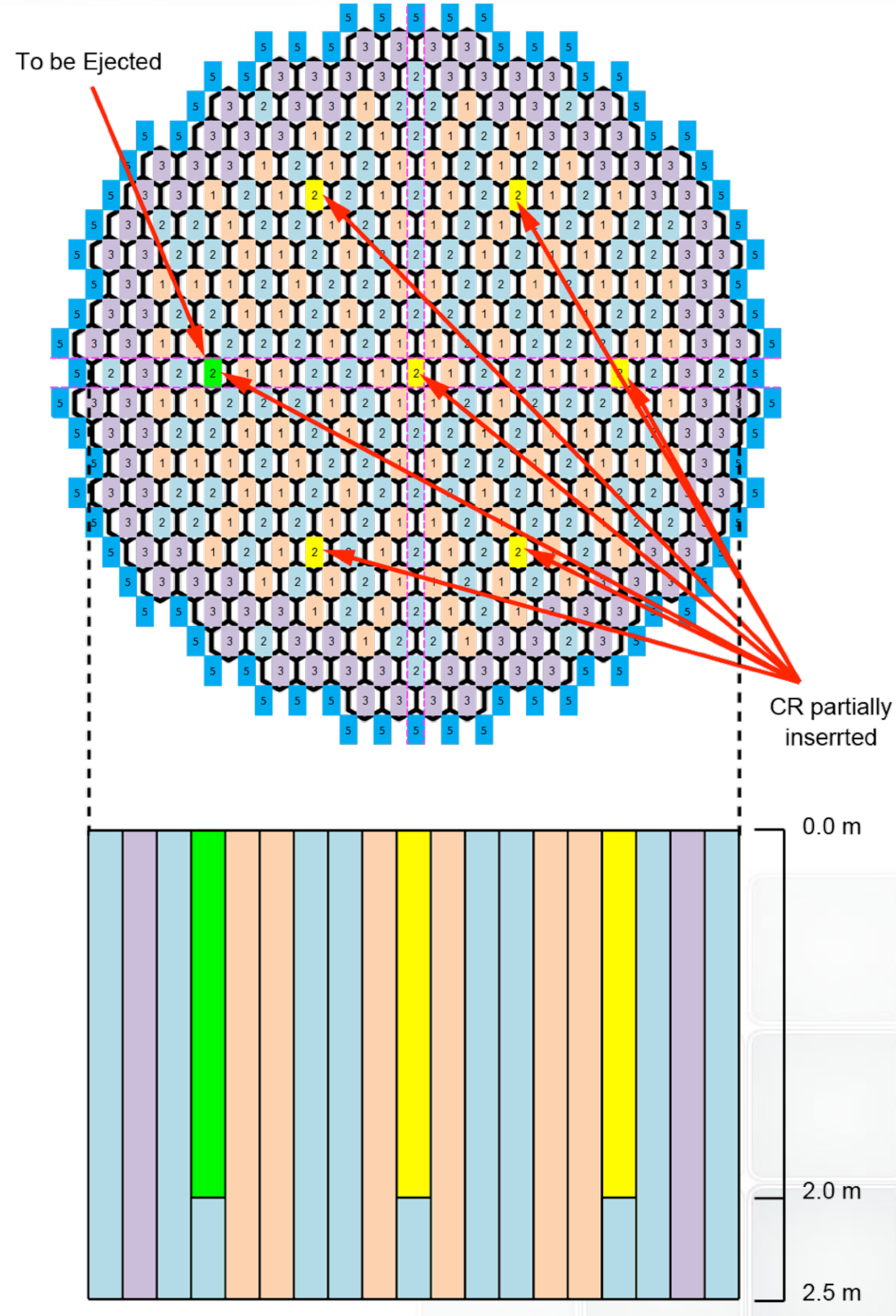
AER DYN003 benchmark

- 3D NK TH CR Ejection simulation
- VVER440 reactor
- 3 Types of Fuel +Ref.
  - “1”: 1.6%
  - “2”: 2.4%
  - “3”: 3.6%
  - “5”: Ref.
- Delayed neutrons groups specified: β = 0.005 (maximize reactivity insertion)



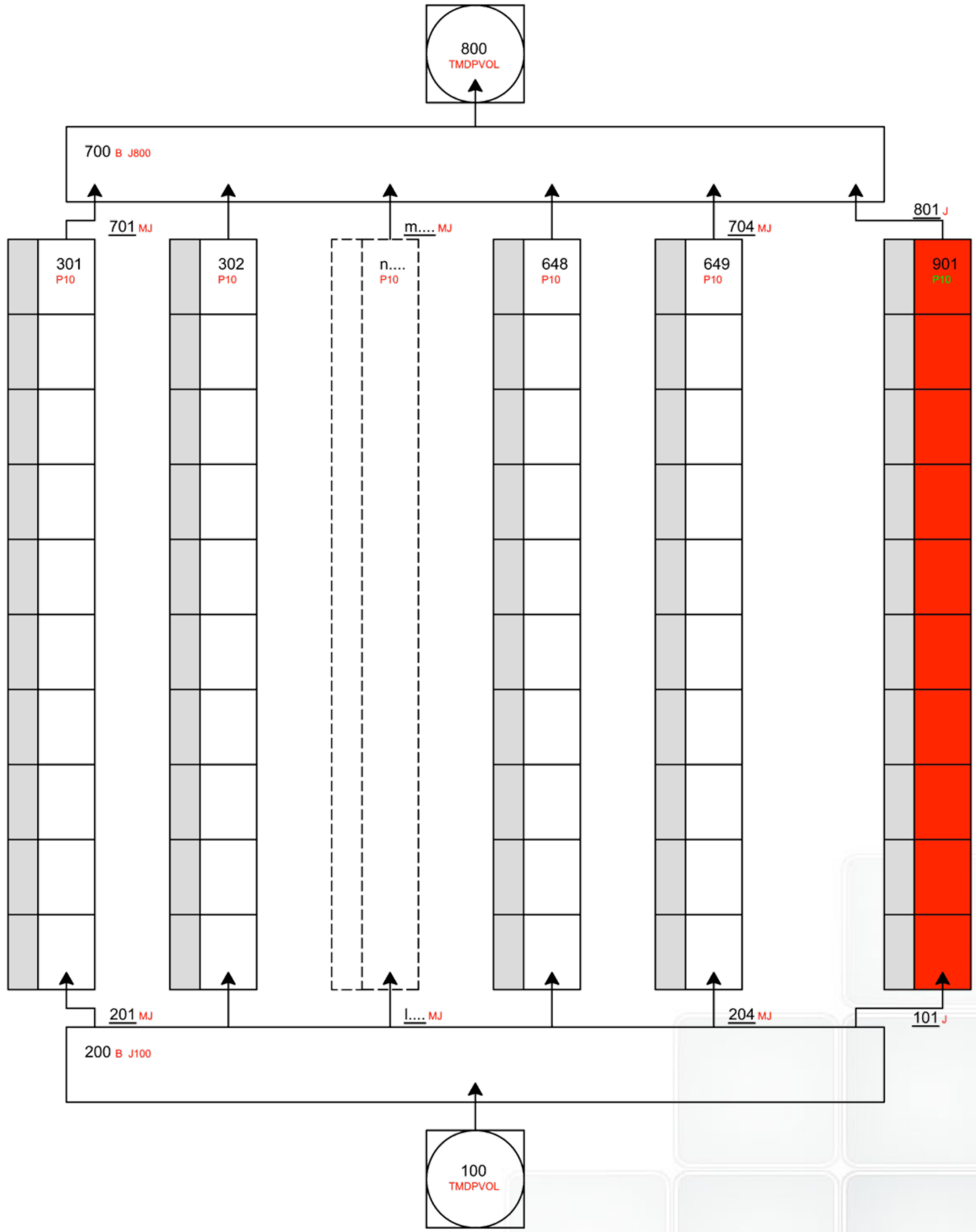
Core model

- Core 250 cm height
- CR partially inserted (2m)
- Eccentric CR ejected in 0.16 sec., speed = 12.5 m/s
- Feedbacks described by the following dependences:
  - $\Sigma_i = \Sigma_{i,0} + a_i (\sqrt{T_f} - \sqrt{T_{f,0}})$
  - $\Sigma_i = \Sigma_{i,0} + b_i (\rho_c - \rho_{c,0})$
- 10.0 seconds simulation to be run
- 22 Axial layers
- Active zone of 20x12.5 cm
- Bottom and Top reflector of 25 cm
- Two BC for Reflector: XSections, Albedo



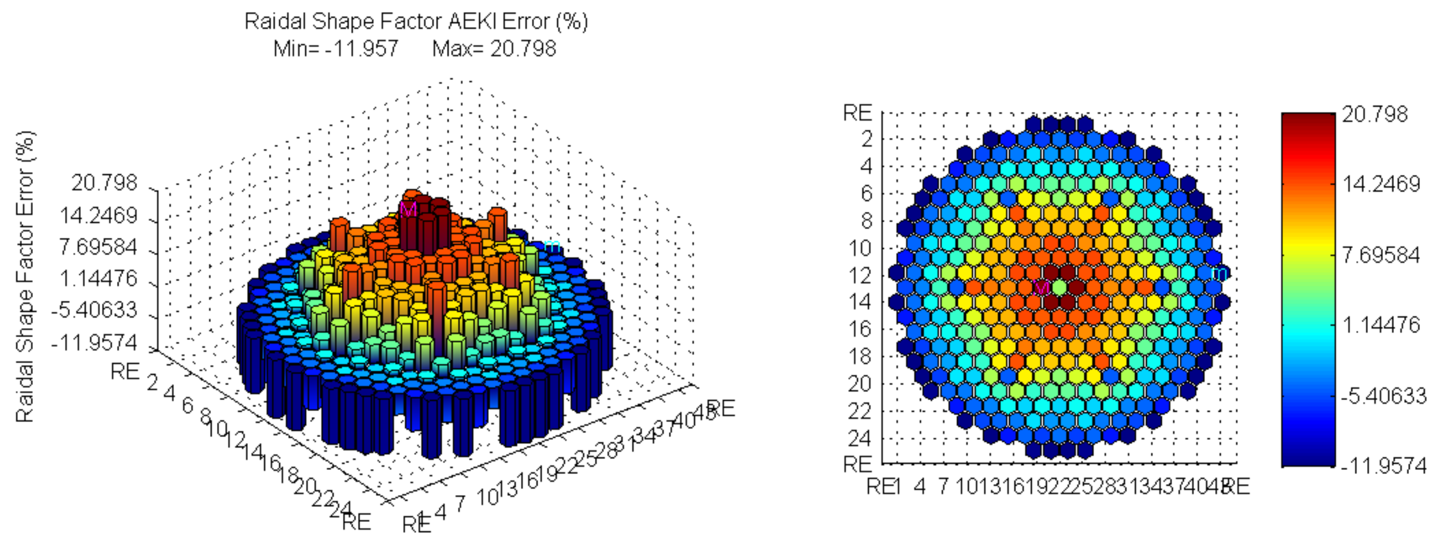
Core model

- Full core, coupled model 349 thermal-hydraulic channels
- 1 hot channel with the power of the hottest channel multiplied for 1.25
- Imposed Inlet and outlet pressure

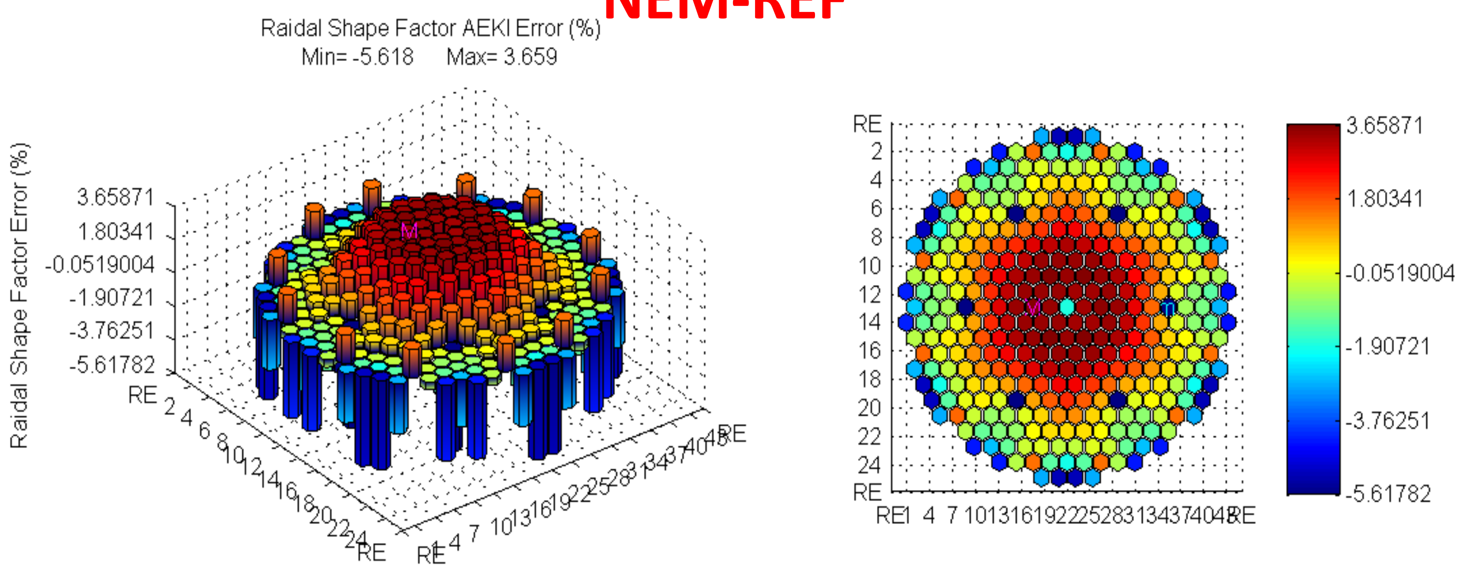


Steady State – Radial Power Distribution

- ***Reflector BC:*** Steady state comparison with independent solution



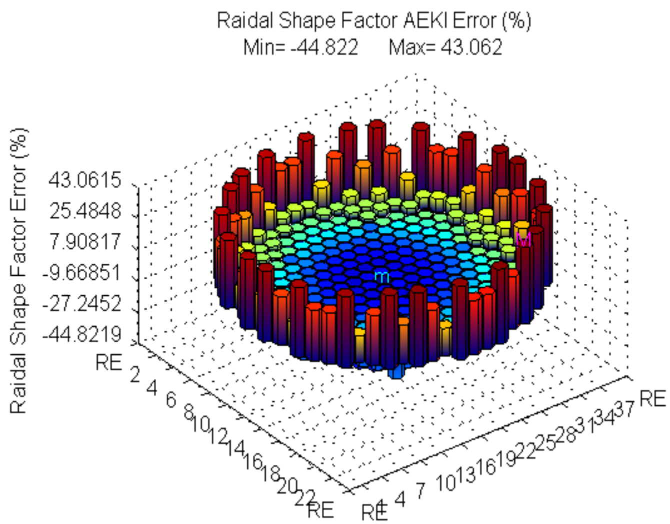
NEM-REF

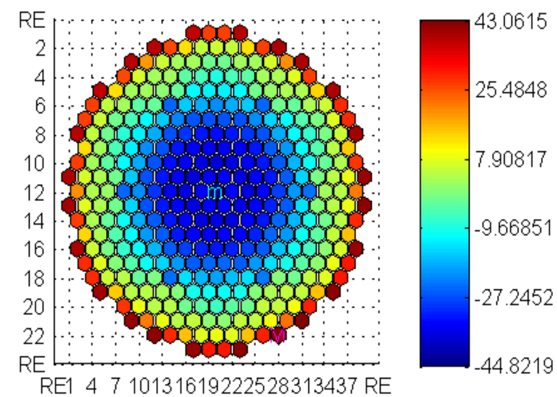


TPEN-REF

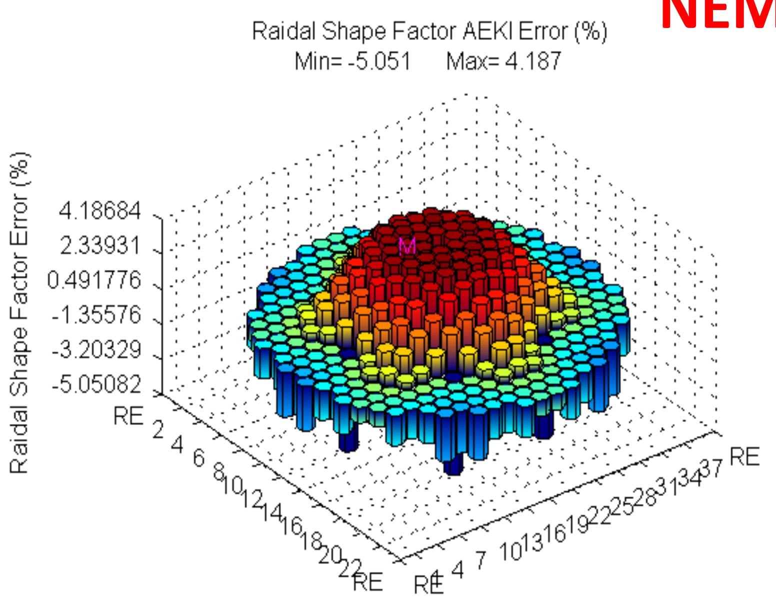
Steady State – Radial Power Distribution

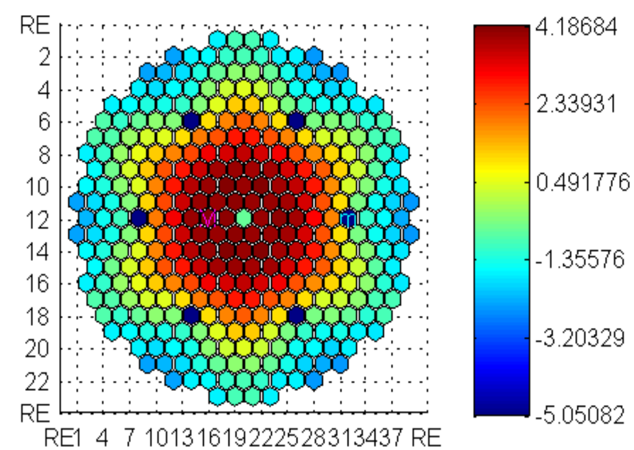
- ***Equivalent albedo BC***: Steady state comparison with independent solution





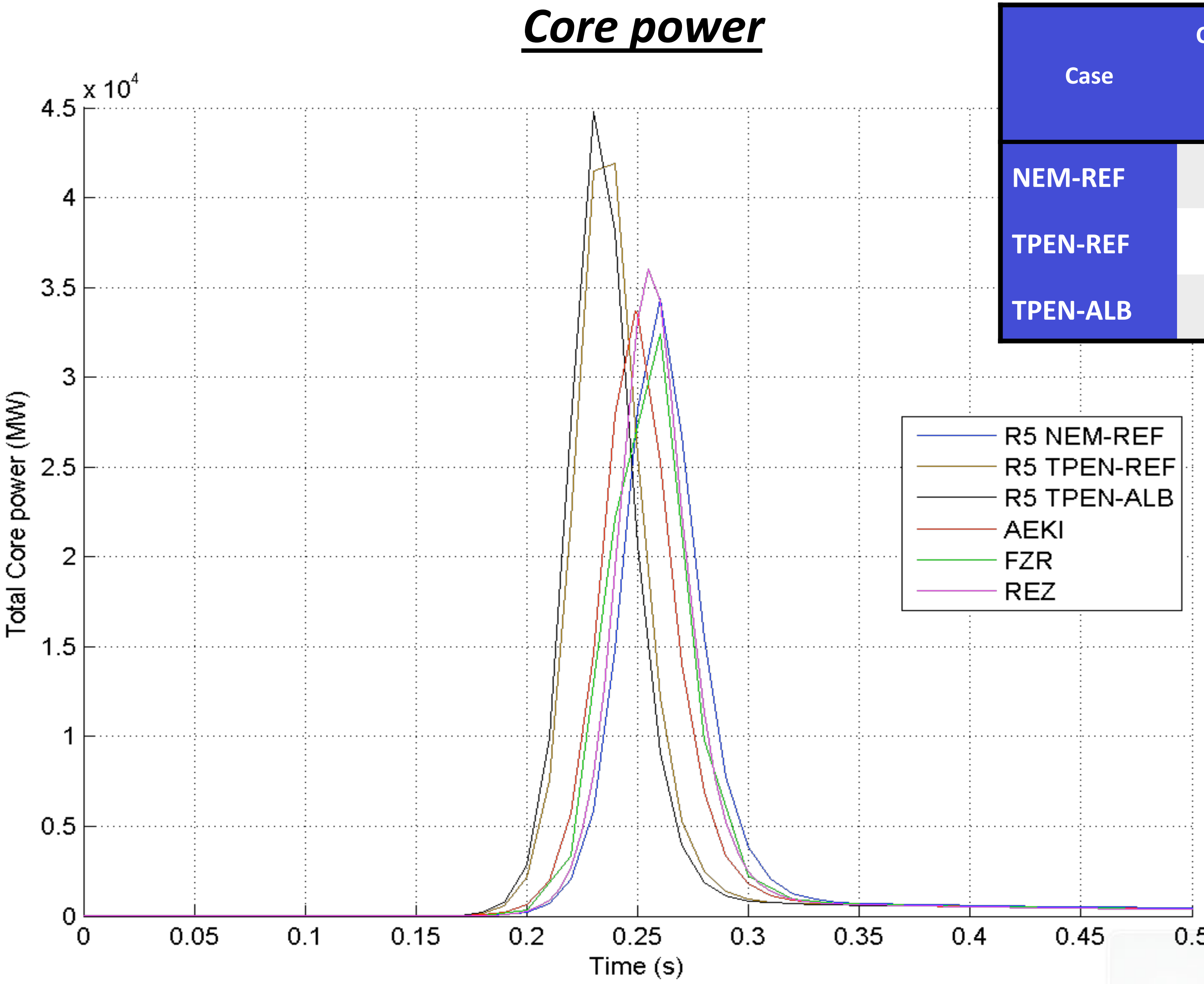
NEM-REF





TPEN-REF

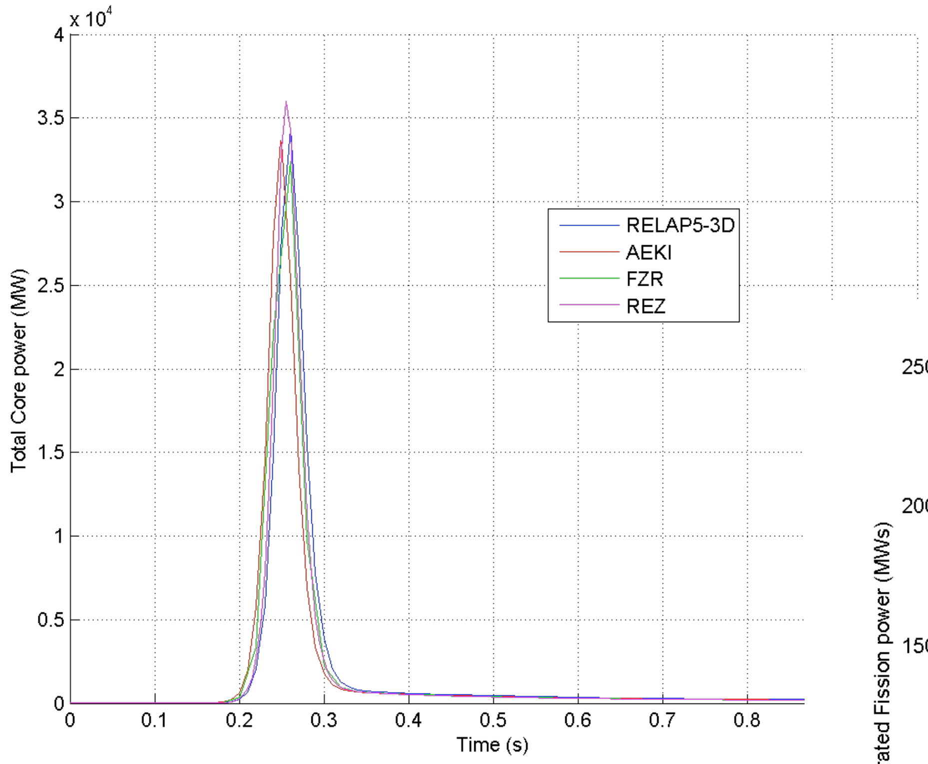
Transient: Core Power

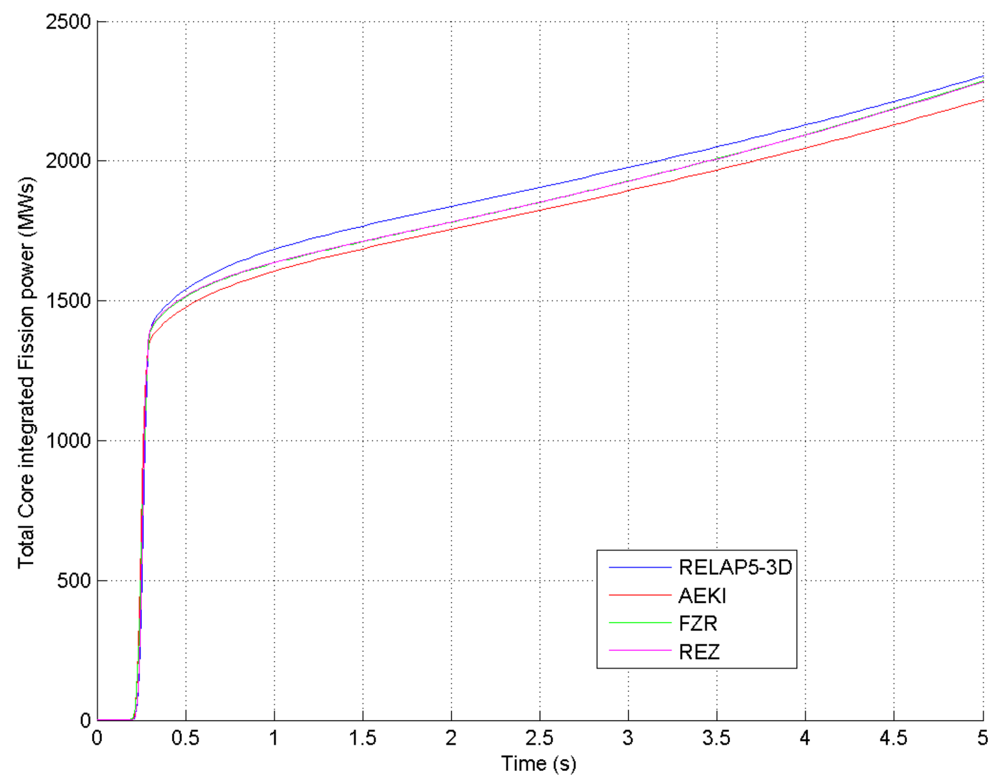


Case	CR worth "ρ↓0↑" ($)	Rel. Error (%)
NEM-REF	1.9037	-3.31
TPEN-REF	2.0666	5.0751
TPEN-ALB	2.075	5.5013

Transient: Core Power

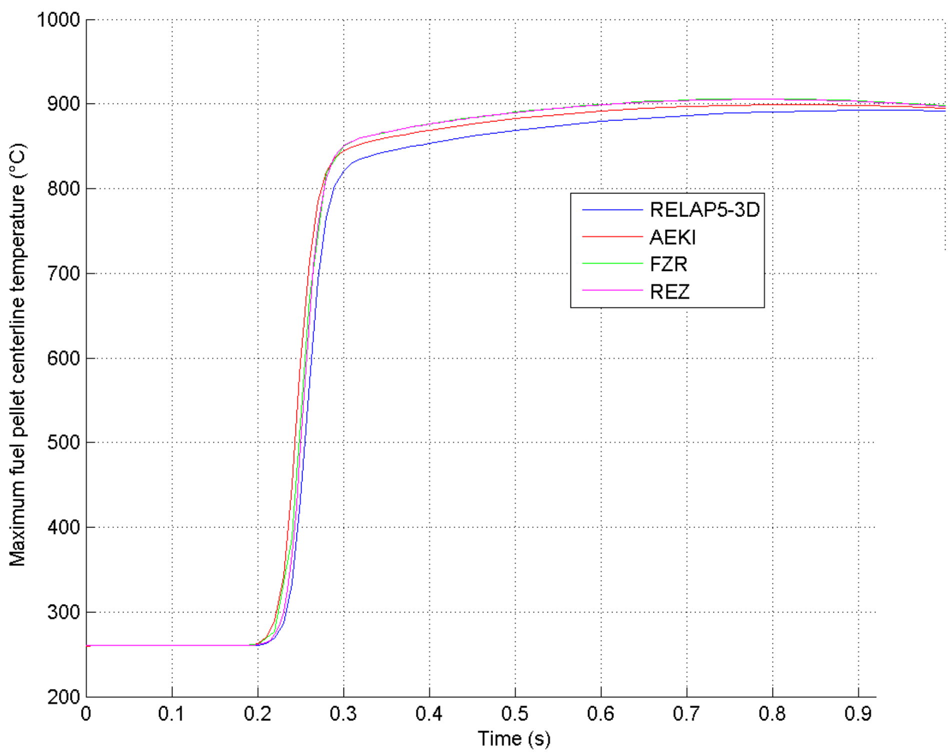
- NEM-REF→ Best Total core power prediction during transient

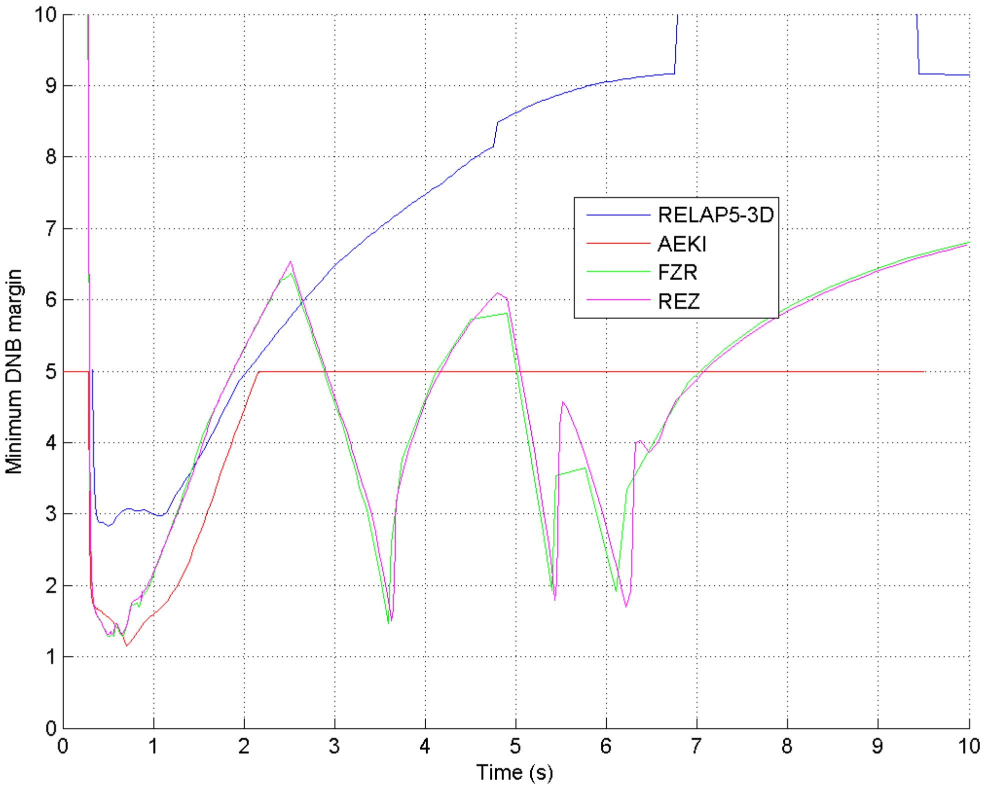




Transient analysis results

- **NEM-REF** Maximum fuel pellet centerline temperature & Minimum DNB margin

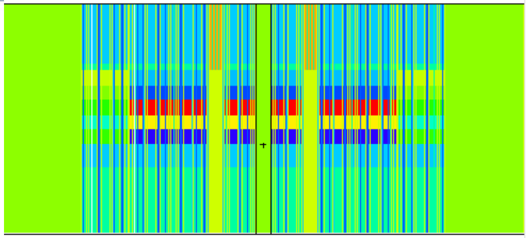




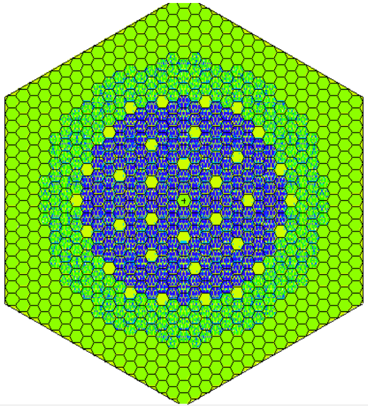
Conclusions on AER-DYN003 activity

- CR ejection event for VVER440 reproduced by RELAP5-3D
- Good agreement for TH calculations, R5-3D less conservative than the other TH modules
- Some discrepancies between the RELAP5-3D and the independent solutions
  - **NEM** has **larger deviation for the SS** compared to the reference solution but…**correctly predict the transient** (power peak magnitude and timing)
  - **TPEN** has **small deviation for the SS** compared to the reference solution but..**overpredict and anticipate** the power peak

Gen IV: EC FP7 PELGRIMM PROJECT: TH contribution



1. Set up of a R5-3D© nodalization of CP-ESFR
   for fast steady state and transient analysis
   - **Main features**: 8 channels core; 1 equivalent MCP and HEX
   - **Status**: nodalization development (completed)

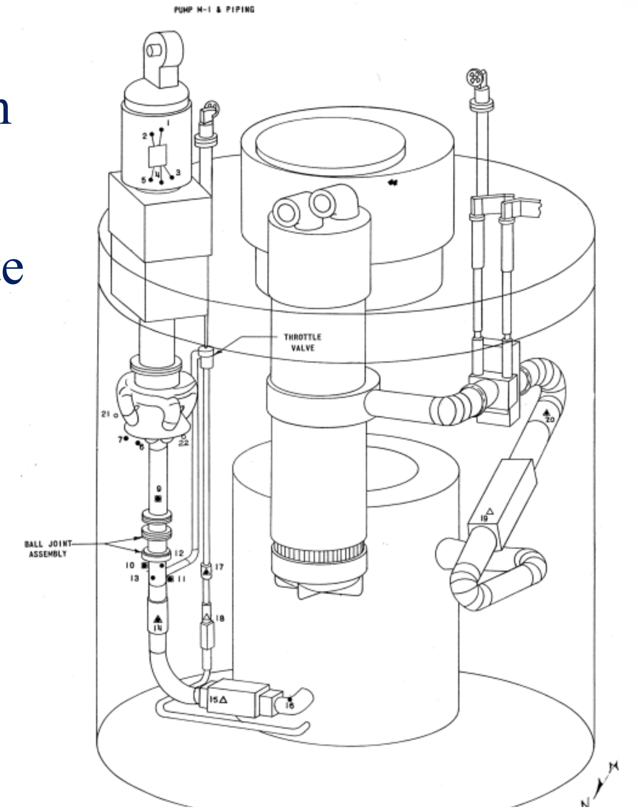


2. Set up of a R5-3D© nodalization for detailed core study, *modeling from MCP outlet to core outlet*
   - **Main features**: 3D TH model, core channel by channel model
   - **Radial/axial power distribution →** from detailed Monte Carlo MCNPX code calculations
   - **Status**: Nodalization development (in progress).
     Qualification of FA pressure drop and heat exchange (completed)
3. Set up of a R5-3D© and "Transuranus" code model for
   - performing subchannel analysis aimed at evaluating FA performances and BIC for fuel pin behavior calculations
   - executing fuel pin calculations

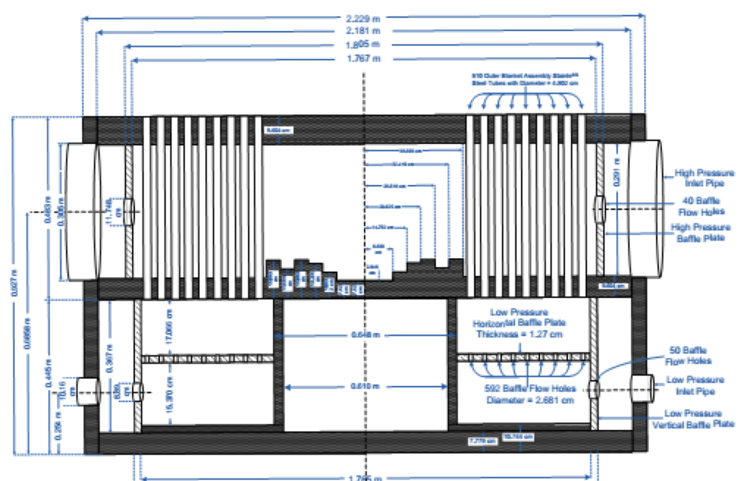
Gen. IV: IAEA EBR-II Benchmark

The aim of the activity is to **validate** the numerical tools (i.e. TH-SYS and coarse mesh CFD codes) and the methodology to perform safety analysis of fast reactor systems

- Blind calculations and post analysis plus sensitivities to evaluate the accuracy in simulating the transient
- 4 yrs program from kick off Meeting (June 2012)

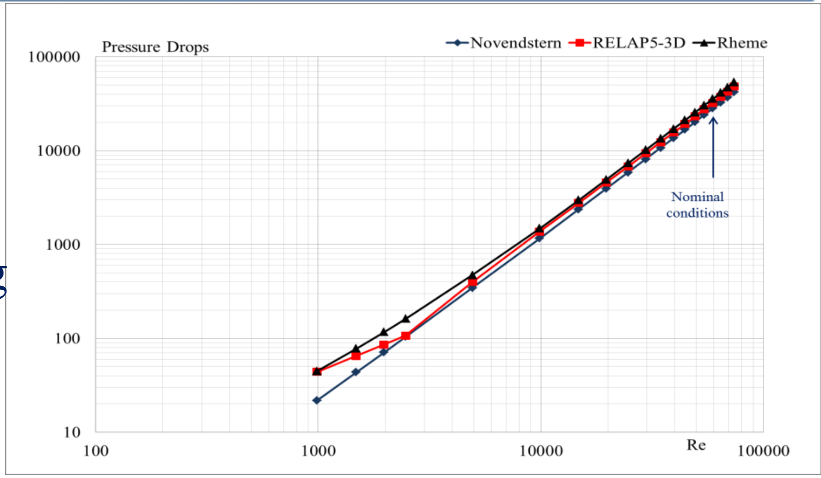


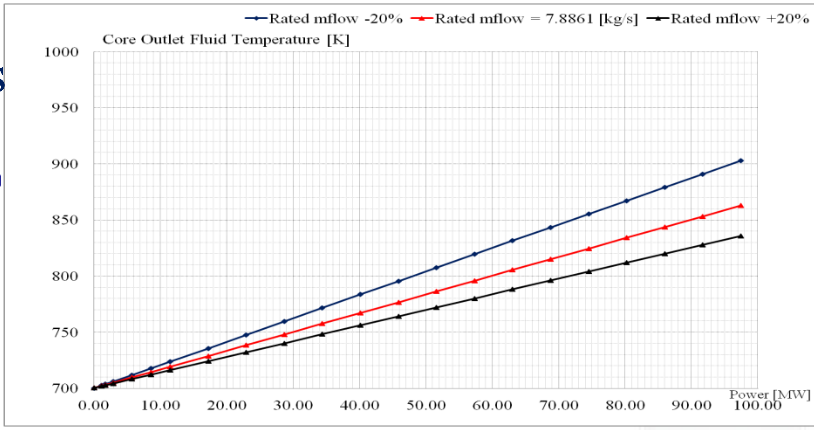
- Current nodalization features
  - EBR-II primary system modeled with
    - 1 MULTID [R=6, Θ=12; z=23]
    - 127 pipes → the 127 driver channels
    - Outer blanket zone modeled with 24 eq. tubes (i.e. 12 eq. reflector channels; 12 blanket)
    - Z-pipe; HEX, pumps and high and low pressure line modeled with 1D components.
  - Secondary side modeled with 1D components

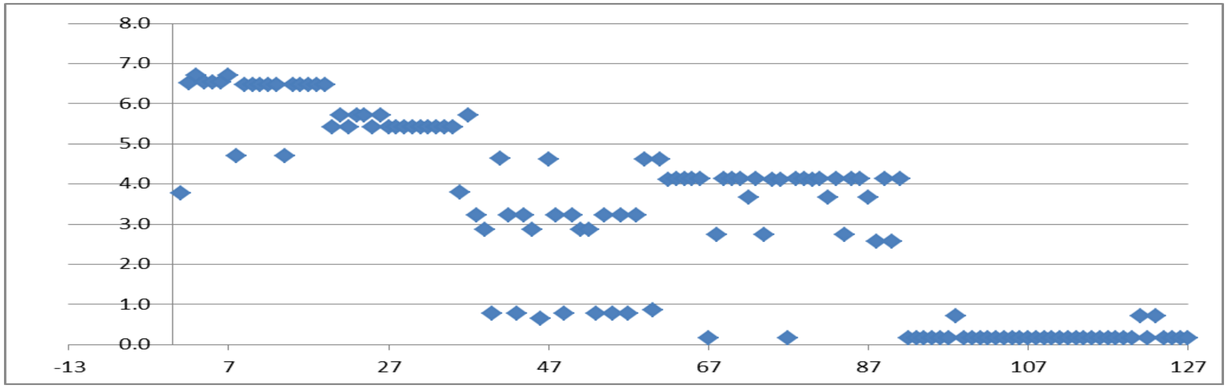


IAEA EBR-II Benchmark

- Current status
  - Nodalization of EBR-II by RELAP5-3D code under development (i.e. TH part + HS of core and SG completed; passive HS and control being completed)
  - Fuel channels pressure drops and heat transfer performances evaluated
  - Flow distribution at fuel channel inlet in progress
  - Possible future coupling with **PHISICS** for **3D NK TH** transient simulations







Conclusion & future steps

- ENEA is using R5-3D code as the reference tool for NPP simulation
- Participating to international benchmarking activities:
  - OECD/NEA Oskarshamn-2 BWR
  - AER "DYN-003"
  - IAEA "EBR-II"
- Using R5-3D in EC funded project for Gen. IV fuel development (**PELGRIMM** project)
- Future works (in collaboration with INL): **PHISICS**/**R5-3D** V&V and development