Advancements of PHISICS / RELAP5-3D Package for Time-Dependent Transient Calculations

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Outline

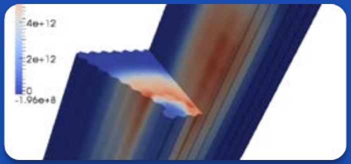
- PHISICS-RELAP5-3D overview
  - Modules
  - Coupling scheme

- Improvements for Time-dependent analysis
  - Time step decoupling
  - Time step adaptivity
  - Perturbation Module – Quasi Static approach
  - Decay-heat surrogate models

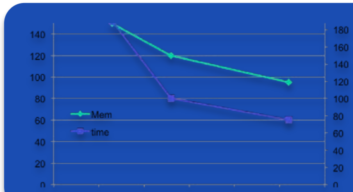
- Application of PHISICS/RELAP5-3D by University of Rome “La Sapienza”:
  - Generation IV ALFRED concept

Software purpose

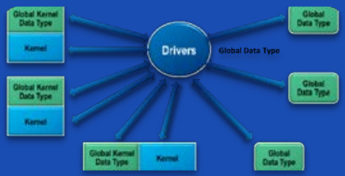
Parallel and **H**ighly **I**nnovative **S**imulation for the **I**NL **C**ode **S**ystem (PHISICS) principal purposes are:



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

Modules

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

MIXER

MRTAU
Multi-Reactor Transmutation Analysis Utility

CRITICALITY

TIME INTEGRATOR

SPH XS Correction

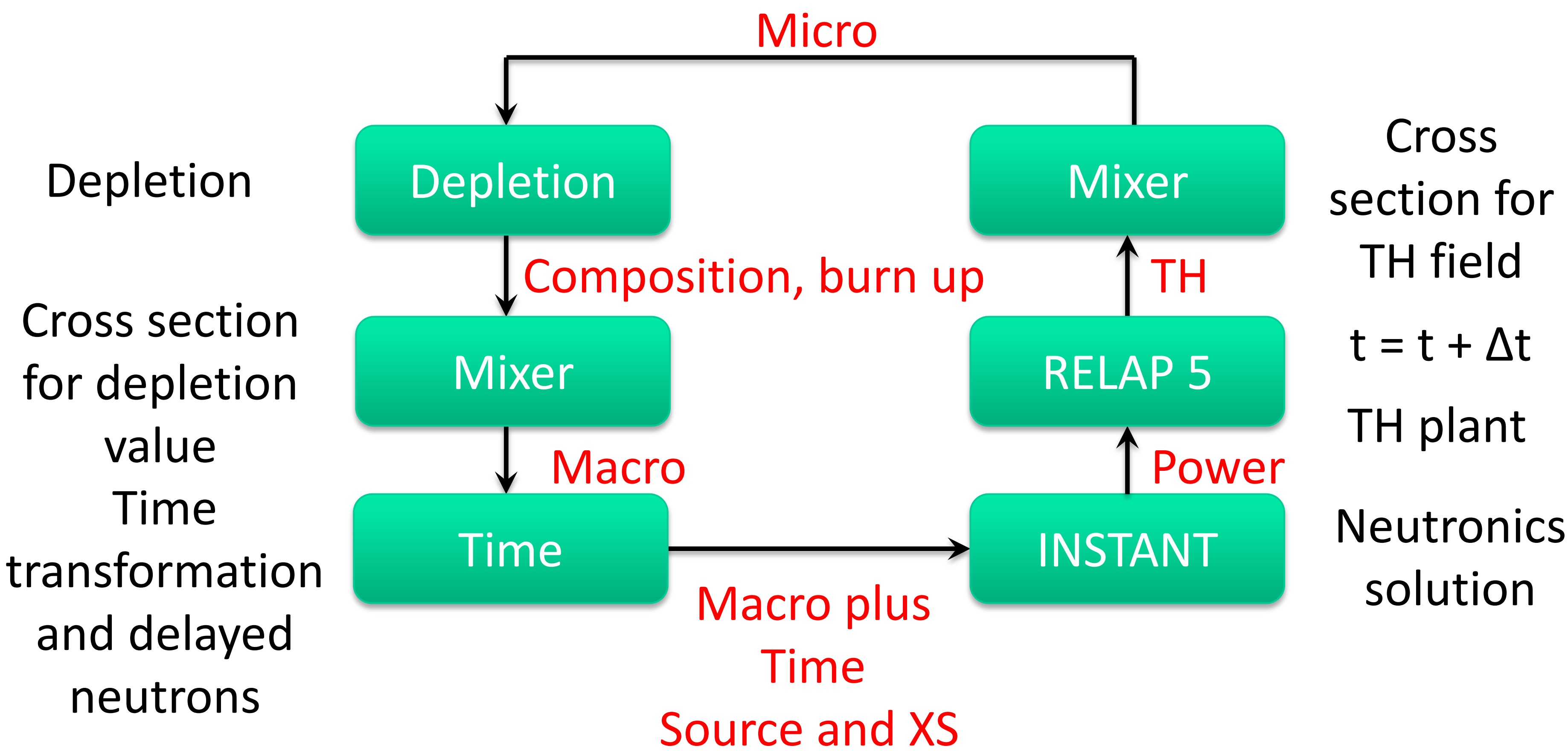
Perturbation Theory

RELAP5-3D coupling

Fuel Management

PARALLEL (MPI) ENVIRONMENT

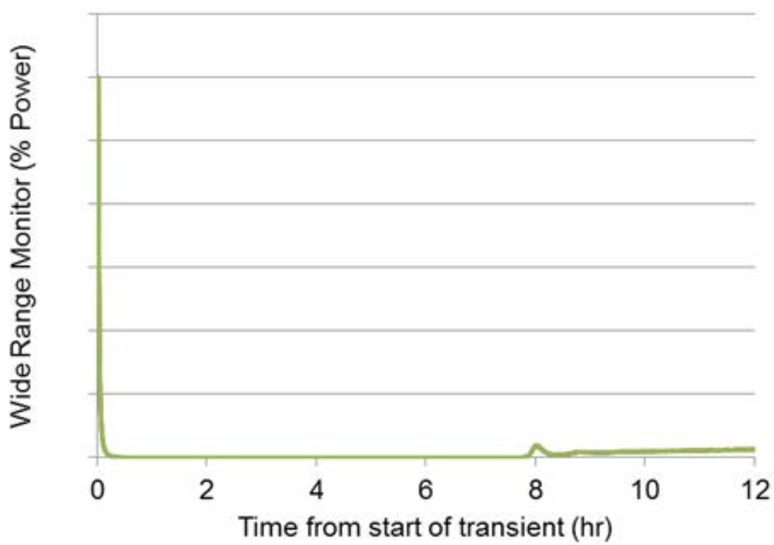
Time-dependent simulation scheme

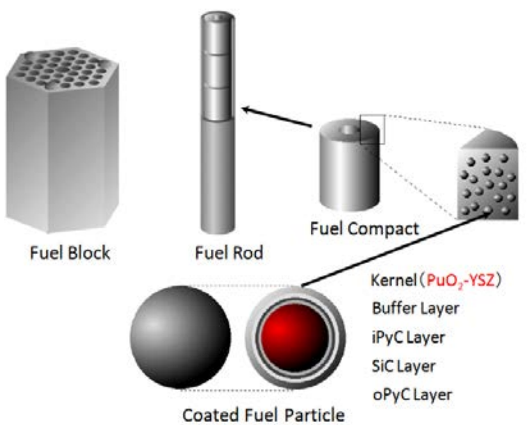


The HTTR and LOFC transient

- December 2010, JAEA performed a LOFC, with automatic reactor trip circuitry disabled.
- When the forced flow stopped, the fuel temperature increased → negative reactivity → sub-critical within the first minute.
- Critical again after 8h for the Xe^{135} decay

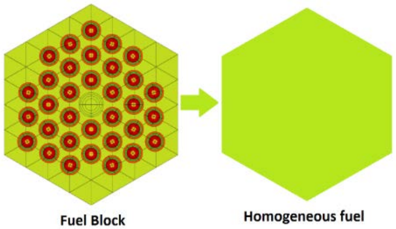
Reactor main parameters	
Coolant	Helium
Outlet coolant temperature	320°C
Inlet coolant temperature	180°C
Primary pressure	2.774 MPa
Average power density	2.5 W/cm^3
Core diameter	2.9 m
Outlet coolant temperature	320°C
Inlet coolant temperature	180°C

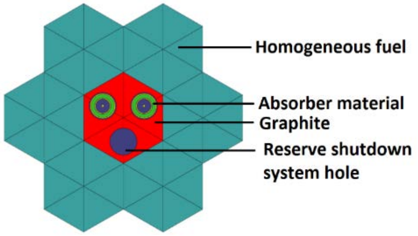


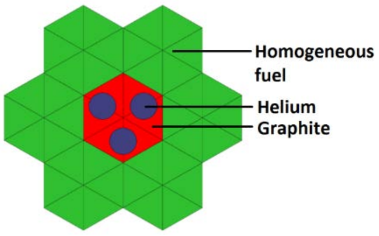


HTTR 3D NK and TH model

- TH model: One TH channel for each radial ring + conduction and radiation model.
- NK model: 3D Hex assembly by assembly nodalization with 5 axial meshes for the active zone
- XSec: mixed XSec generated using **DRAGON5**
  - Macro XSec for the FUEL.
  - Micro XSec with Xe^{135} and I^{135}.
  - Tabulated respect to Fuel, Moderator temperature, and Xe^{135} concentration

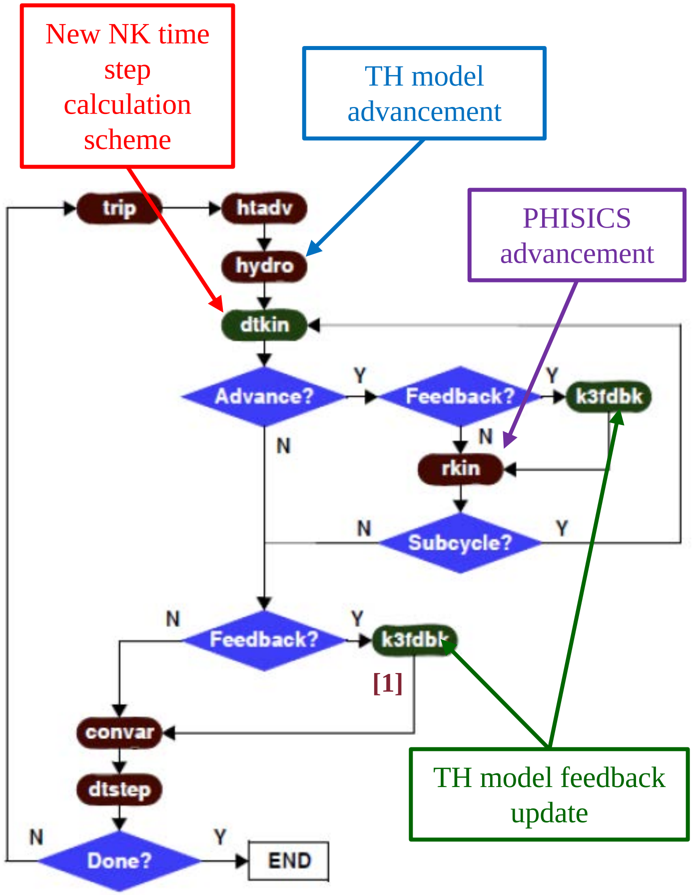






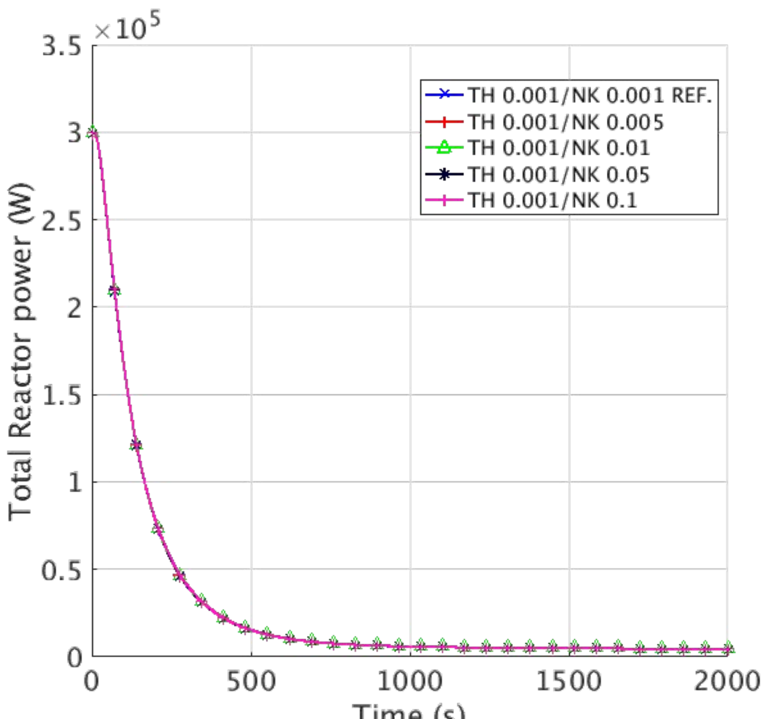
Time-dependent: Time-step decoupling

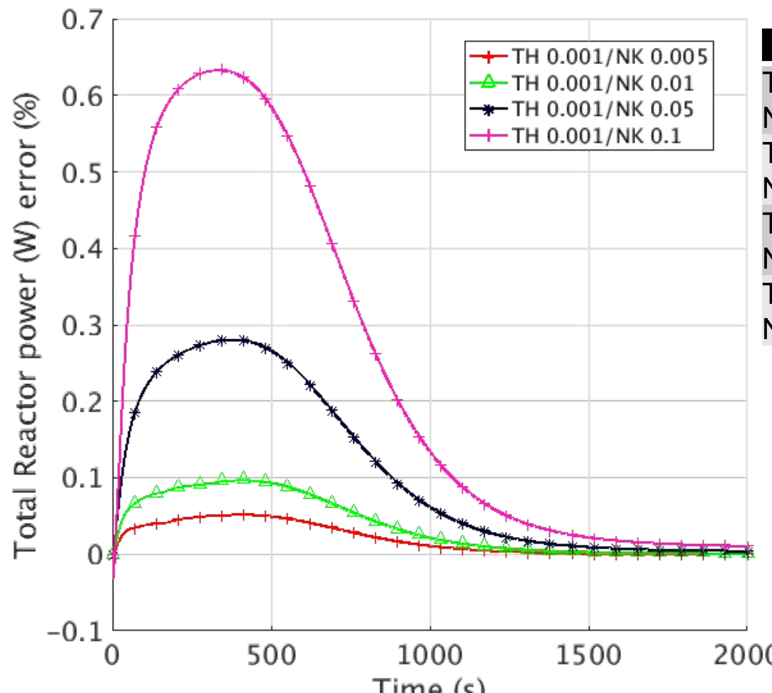
- The RELAP5-3D© decoupling scheme developed for NESTLE has been used→ Minor modifications applied to the PHISICS code in order to use the new NK time step for MRTAU (depletion) and for the time evolution scheme.
- To verify the functionality of the modifications with a simplified model, using the same PHISICS modules→ Reduced version of HTTR model→ one ring and one NK reflected assembly 15 axial nodes.



Constant NK Time step results HTGR model

- Reference solution $\Delta t_{NK}=\Delta t_{TH}$=1e-3s for 2000 s transient (2E+6 iterations)
- The Δt_{TH} has been kept to 1e-3s to ensure that the TH solution is fully converged and does not introduce error in the calculations.





Case	Speedup
TH 0.001 NK 0.005	3
TH 0.001 NK 0.01	5
TH 0.001 NK 0.05	8
TH 0.001 NK 0.1	14

Time-dependent: Time-step adaptivity

$$\left.\frac{\partial \phi_r^g}{\partial t}\right|_{t=t_n} = \frac{\phi_r^{g(n)} - \phi_r^{g(n-1)}}{\Delta t_n} + e_\phi^{(n)}$$

$$e_\phi^{(n)} = \frac{\Delta t_n}{2} \left.\frac{\partial^2 \phi_r^g}{\partial t^2}\right|_{t=t_n} + O(\Delta t_n^2) \qquad e_\phi^{(n)} \Delta t_n \leq \tau$$

Predicted Time step

$$\Delta t_p = \Delta t_n \leq \sqrt{2\tau \left|\frac{\partial^2 \phi_r^g}{\partial t^2}\right|^{-1}}$$

Possible additional constrains

1) $\Delta t_1 \leq \Delta t_p \leq \Delta t_2$
2) Δt_p multiple of the Δt_{TH}

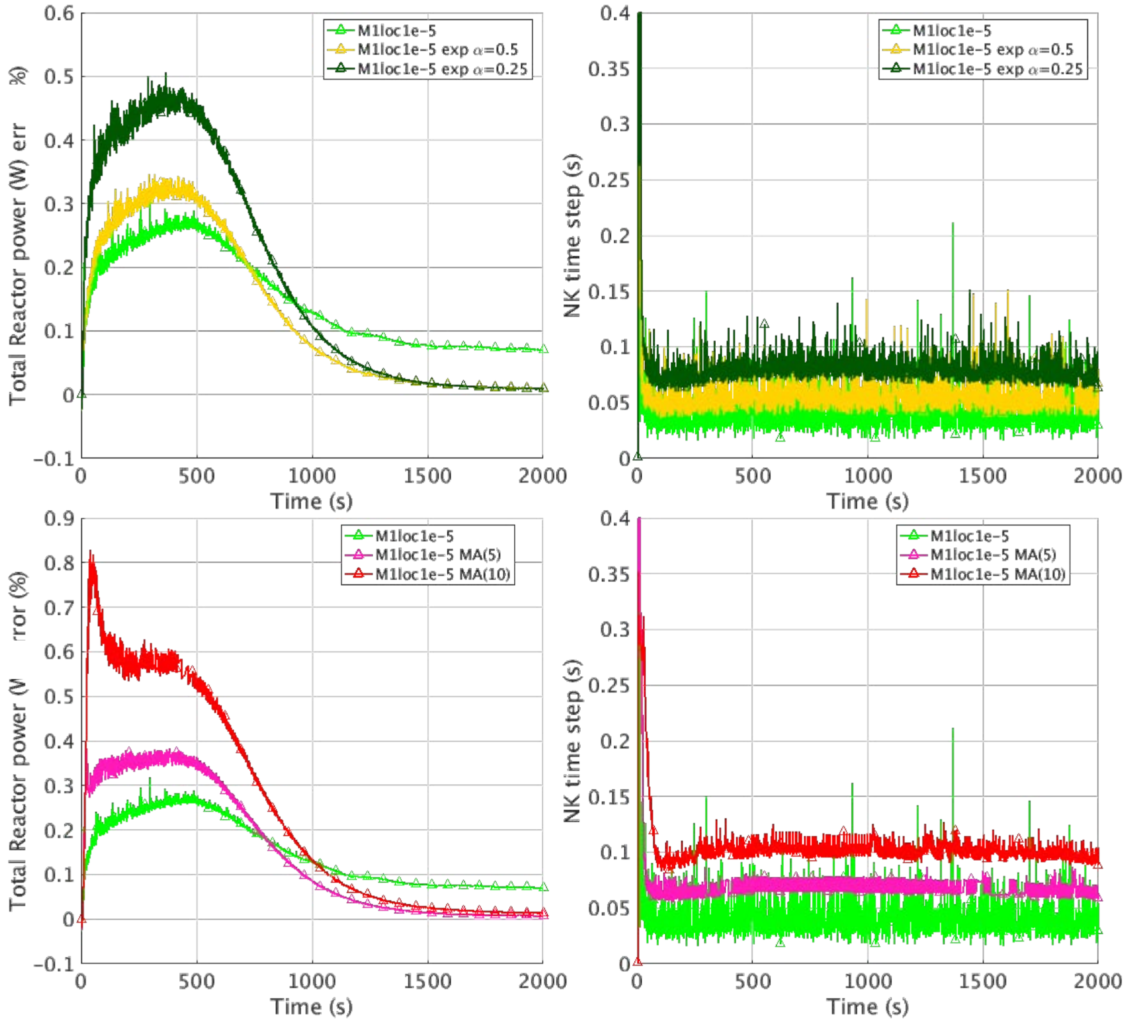
Methodology 1 (M1)

$$\left.\frac{\partial^2 \phi_r^g}{\partial t^2}\right|_{t=t_n} \approx \frac{\Delta t_{n-1} \phi_r^{g(n)} - (\Delta t_{n-1} + \Delta t_n) \phi_r^{g(n-1)} + \Delta t_n \phi_r^{g(n-2)}}{\Delta t_{n-1} \Delta t_n (\Delta t_{n-1} + \Delta t_n)}$$

Methodology 2 (M2)

$$\left.\frac{\partial^2 \phi_r^g}{\partial t^2}\right|_{t=t_n} \approx \frac{\Delta t_{n-1} \phi_r^{g(n)} - (\Delta t_{n-1} + \Delta t_n) \phi_r^{g(n-1)} + \Delta t_n \phi_r^{g(n-2)}}{\Delta t_n \Delta t_n \Delta t_{n-1}}$$

Moving average (MA) and Exponential smoothing on NK *Δt* prediction



Exponential smoothing

$$\Delta t_n = \Delta t_{n-1}(1-\alpha) + \alpha \Delta t_p$$

Moving average MA(N)

$$\Delta t_n = \frac{\sum_{i=1}^{N-1} \Delta t_{n-i} + \Delta t_p}{N}$$

Case	Speedup
M1loc ε=1e-5	**7**
M1loc ε=1e-5 α=0.5	8
M1loc ε=1e-5 α=0.75	11
M1loc ε=1e-5 MA(5)	10
M1loc ε=1e-5 MA(10)	16

Perturbation Module – Quasi Static approach

- The quasi-static approach is a tradeoff in terms of accuracy and computational cost that factorize the flux into an amplitude and a shape function:

$$\Phi_g(\boldsymbol{r},\boldsymbol{\Omega},t) = P(t)\psi_g(\boldsymbol{r},\boldsymbol{\Omega},t)$$

$$\begin{cases} \dfrac{dP(t)}{dt} = \dfrac{\rho(t)-\beta_{eff}}{\Lambda}P(t) + \displaystyle\sum_i \lambda_i C_i(t) + Q(t) \\ \dfrac{dC_i(t)}{dt} = \dfrac{\beta_{eff}}{\Lambda}P(t) - \lambda_i C_i(t) \; i = 1,\dots,N_f \end{cases}$$

- For the computation of the kinetic parameters, a perturbation module has been implemented:

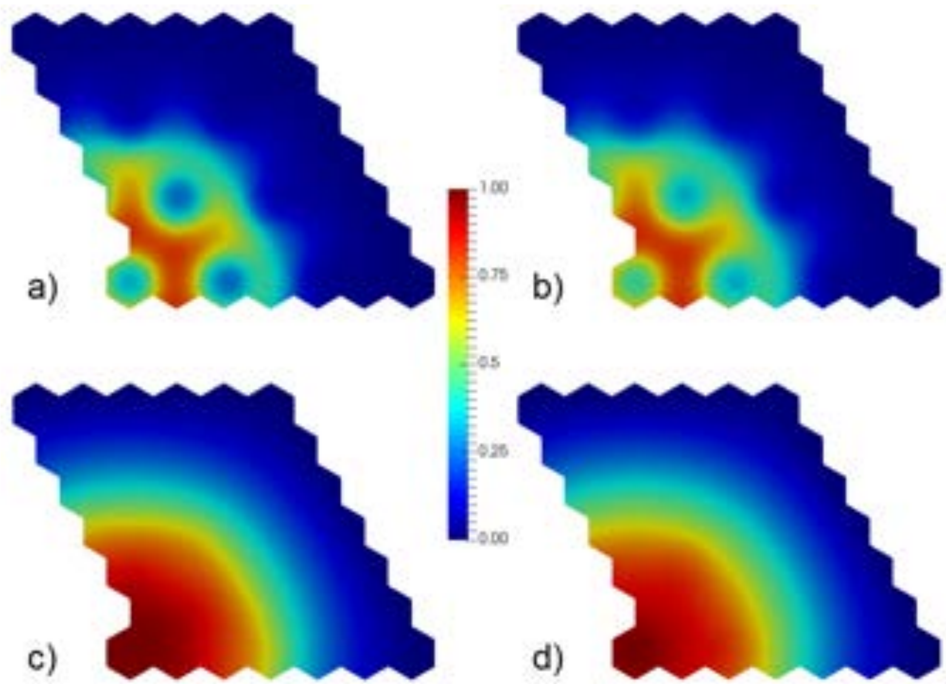
$$\rho_{direct} = \frac{\delta k}{k' k}$$

$$\rho_{exact} = \frac{\frac{1}{k'}\psi^{*T}\delta F\psi' + \psi^{*T}\delta C\psi' - \psi^{*T}\delta A\psi'}{\psi^{*T}F\psi'}$$

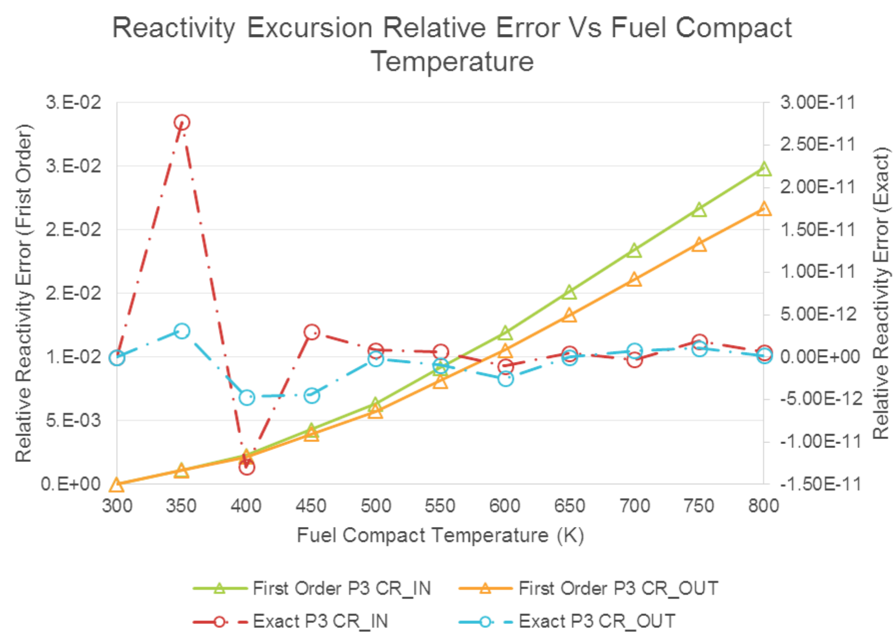
$$\rho_{1^{st}vorder} = \frac{\frac{1}{k}\psi^{*T}\delta F\psi + \psi^{*T}\delta C\psi - \psi^{*T}\delta A\psi}{\psi^{*T}F\psi}$$

Perturbation module – HTTR case

- 10 steps of calculations increasing the fuel compact temperature of 50 degree from 300 K to 800 K
- 10 steps increasing the graphite temperature from 300 K to 800 K



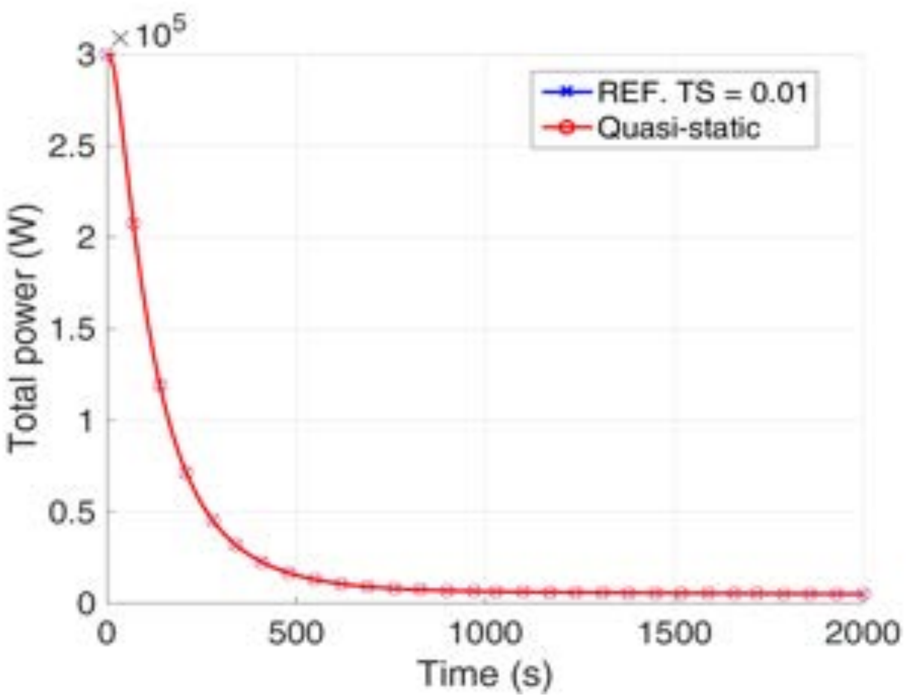
P1 midsection normalized total flux: CR fully in, adjoint a) and direct b) solution; CR fully out, adjoint c) and direct d) solution

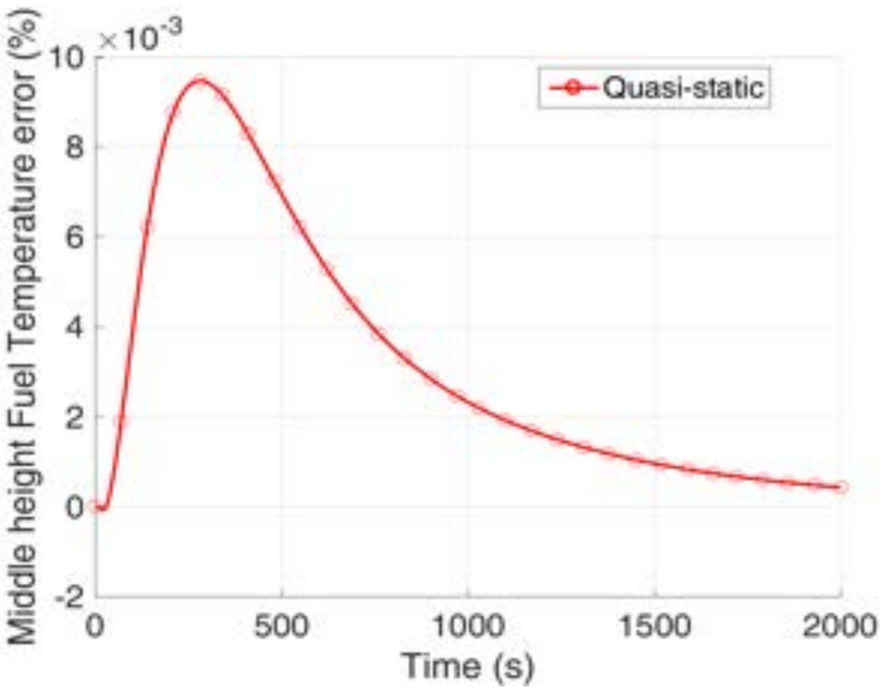


HTTR model, P3 approximation, reactivity excursion relative error vs fuel compact temperature

Quasi-static module – HTTR case

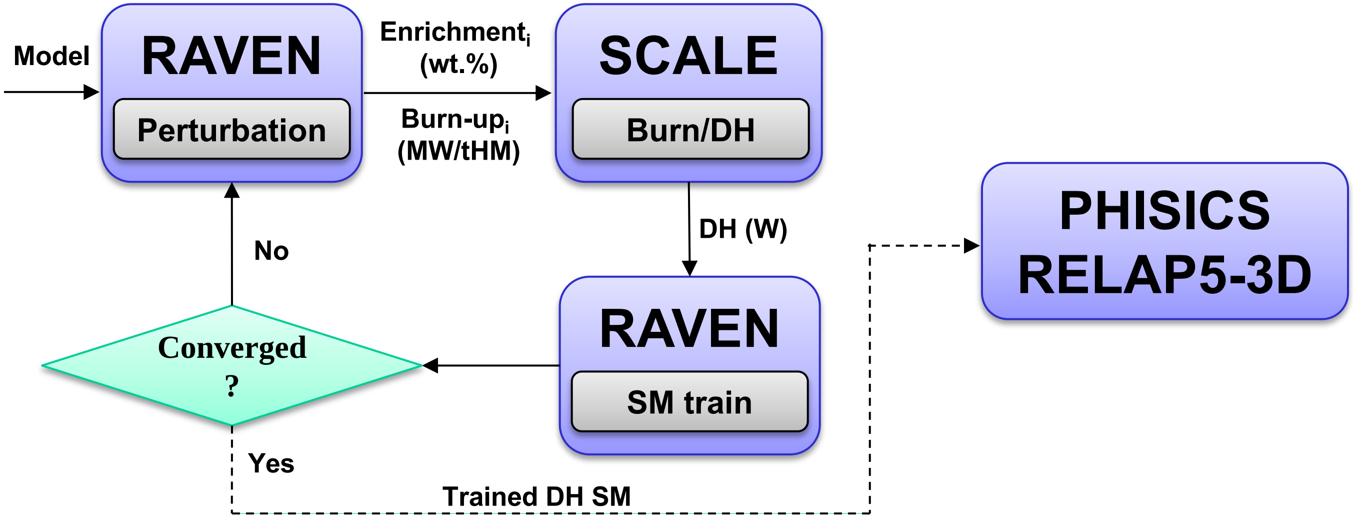
- Reference calculation:
  - default Time-Dependent solver
  - constant time step of 1e-2 s.
- QS calculation:
  - time step of 1e-2 s for the point kinetic
  - update flux and adjoint shape every 10 s





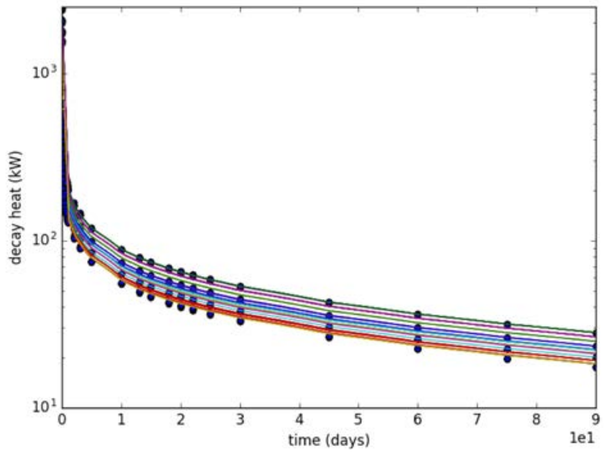
DH Surrogate Model for PHISICS/RELAP5-3D

- Identification of a model able to surrogate the DH evolution after shutdown and during operation
- Requirement:
  - Reasonable prediction accuracy till 3 months in pure decay
  - Ability to capture the main deviation effects determined by field conditions
- Required tools:
  - ***SCALE (TRITON/ORIGEN)***, ***RAVEN***, ***PHISICS/RELAP5-3D***

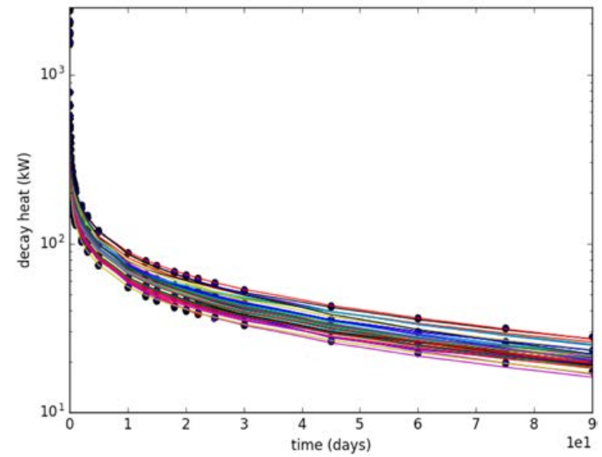


DH for PHISICS/RELAP5-3D - Results

Spline Exponential

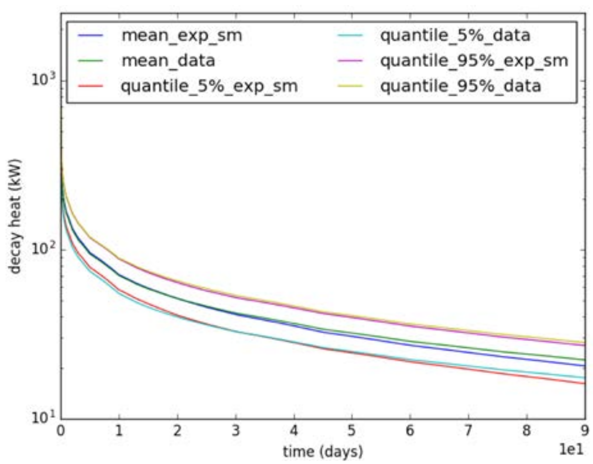


MC SEM predictions (line) vs. original data (scatter)

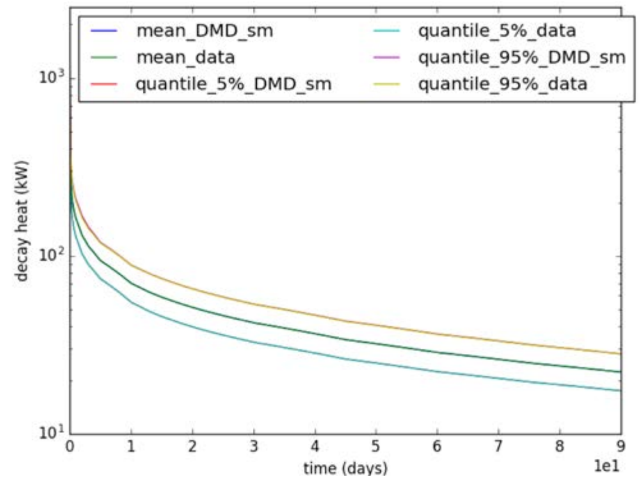


MC DMD prediction (line) vs. original data (scatter)

Dynamic Mode Decomposition



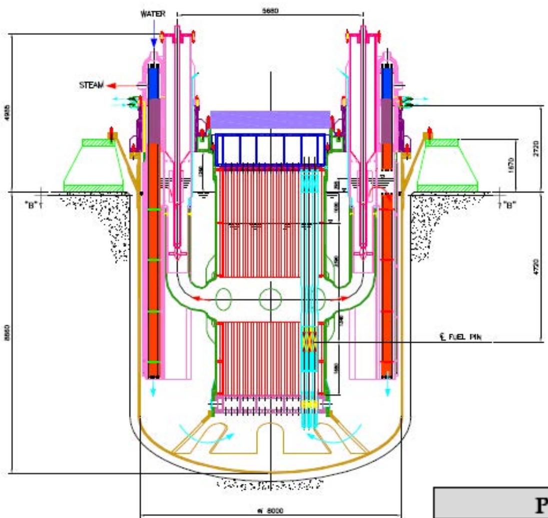
Mean and Quantiles comparison SEM vs. Data

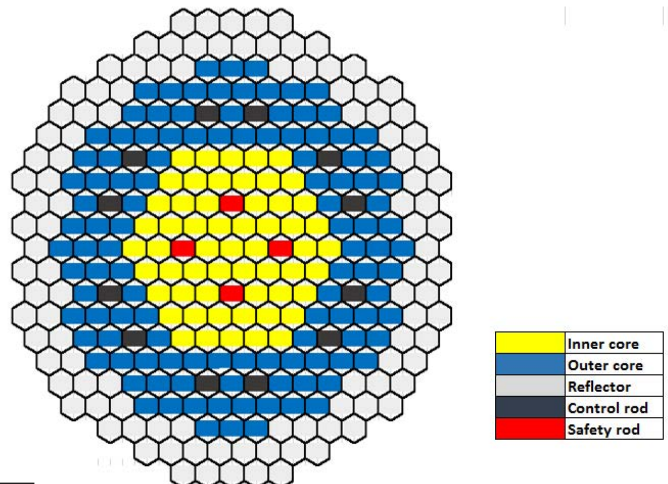


Mean and Quantiles comparison DMD vs. Data

ALFRED TH/NK simulation

- The conceptual design of lead-cooled demonstrator reactor ALFRED was developed in the LEADER EU FP7 project to meet the safety objectives of the GEN IV nuclear energy systems.
- ALFRED is a pool type Pb-cooled fast reactor of 300 MWt.





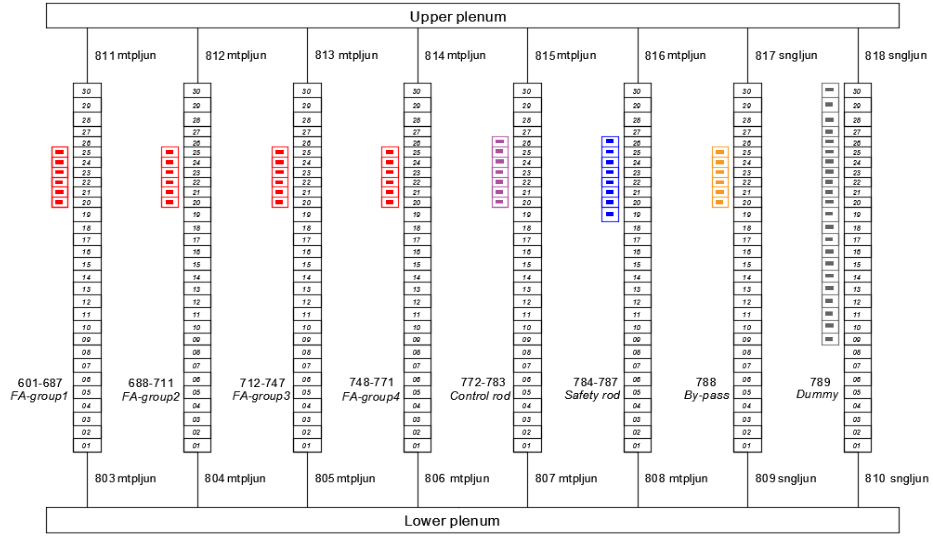
Parameter	Unit	Value
Thermal power	MW	300
Net electrical power	MW	125
Core inlet temperature	°C	400
Core outlet temperature	°C	480
Feedwater temperature	°C	335
Steam temperature	°C	450
Steam pressure	bar	180
Core flow rate	Kg/s	25980
N° of primary loops	#	8
Feedwater flow rate (1SG)	Kg/s	3247.5

- 57 FA for the inner core zone
- 114 FA for the outer core zone
- 108 dummy elements (shield of the vessel)
- 12 control rods FA
- 4 safety rods FA

ALFRED Core Nodalization in RELAP5-3D

- 171 pipes to represent the 171 FAs
- 12 pipes to represent the 12 CRs
- 4 pipes to represent the 4 safety rods
- 1 equivalent pipe to represent the 108 reflector elements
- 1 pipe to model the by-pass channel
- 30 Hydrodynamic volumes

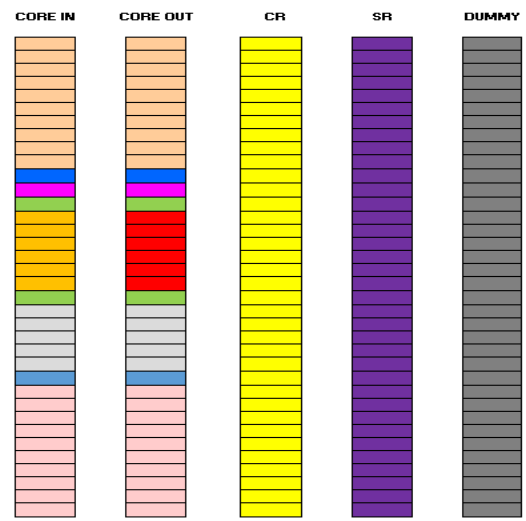
	Power [MW]
Fuel assemblies	294.0
Reflector assemblies	3.1
Control assemblies	1.7
Coolant in the by-pass channel	1.2
Total	300



ALFRED Core Nodalization in PHISICS

Nodalization

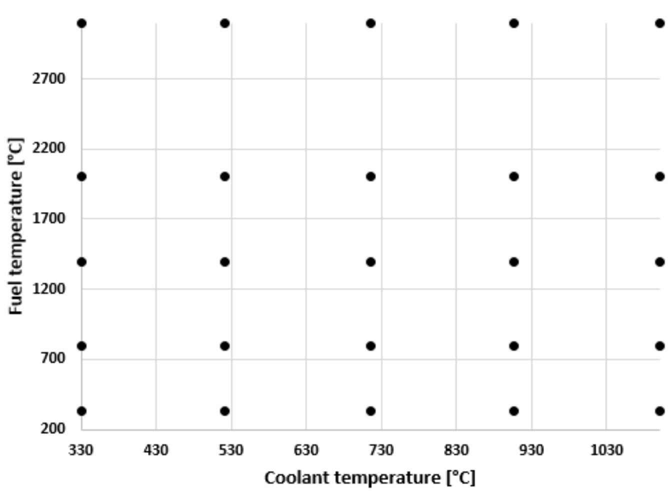
N° of Kinetic Meshes	36
N° of Zone Figures	8
N° Composition Figures	8
N° of Kinetic nodes in a plane	331
N° of kinetic nodes (total)	11916
N° of Neutron groups	33
Core simulated	Full core
Boundary conditions	Non-reentrant current



COMP.FIG. N°	AXIAL MESH N°	ZONE FIG. N°	HEIGHT (m)
8	36	8	0.1
8	35	8	0.1
8	34	8	0.1
8	33	8	0.1
8	32	8	0.1
8	31	8	0.1
8	30	8	0.1
8	29	8	0.1
8	28	8	0.1
8	27	8	0.1
7	26	8	0.0684
6	25	8	0.1216
4	24	8	0.01
5	23	7	0.1
5	22	6	0.1
5	21	5	0.1
5	20	4	0.1
5	19	3	0.1
5	18	2	0.1
4	17	1	0.01
3	16	1	0.11
3	15	1	0.11
3	14	1	0.11
3	13	1	0.11
3	12	1	0.11
2	11	1	0.07
1	10	1	0.1
1	9	1	0.1
1	8	1	0.1
1	7	1	0.1
1	6	1	0.1
1	5	1	0.1
1	4	1	0.1
1	3	1	0.1
1	2	1	0.1
1	1	1	0.1

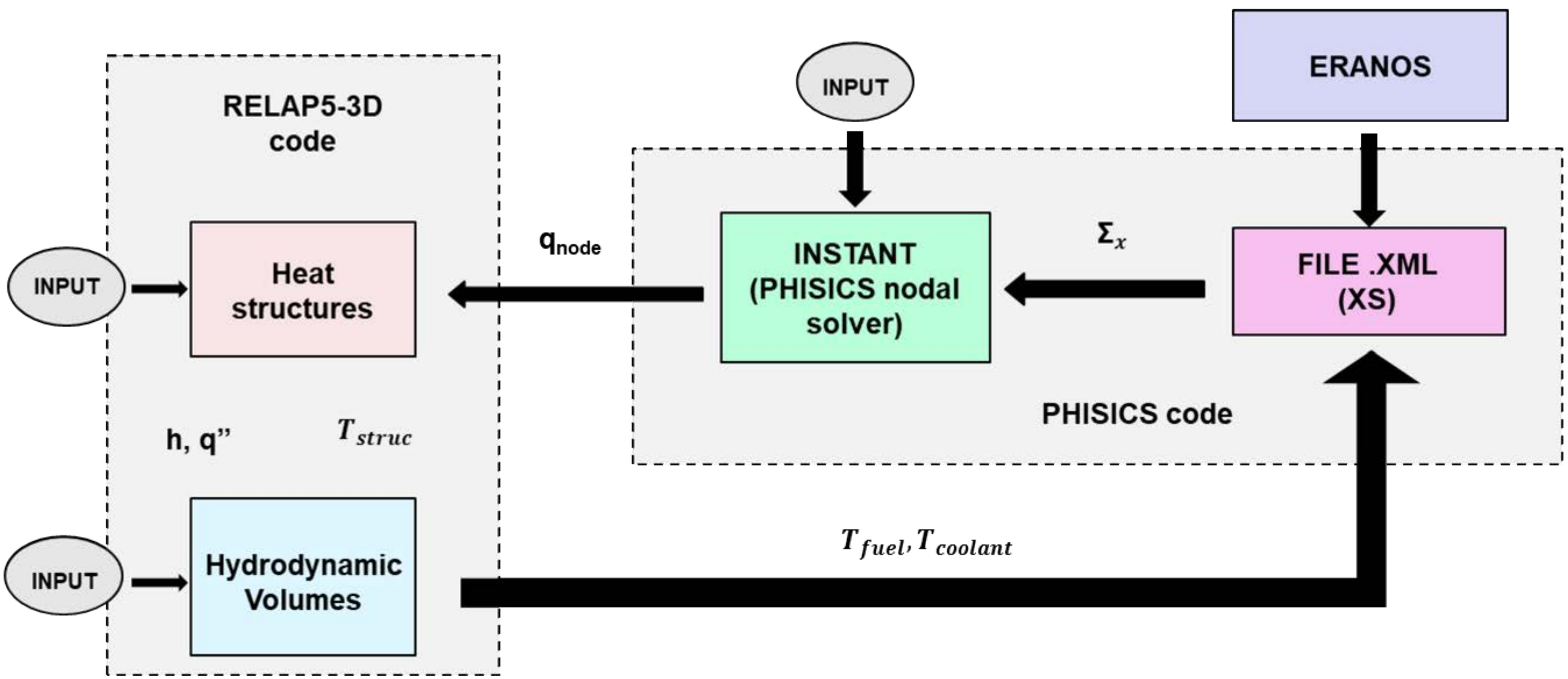
1		CORE 1
2		CORE 2
3		THERMAL INSULATOR
4		SPRING
5		UPPER PLUG
6		LOWER PLENUM
7		FUEL LOWER PLUG
8		CR
9		SR
10		DUMMY
11		TOP
12		BOTTOM

XS tabulation

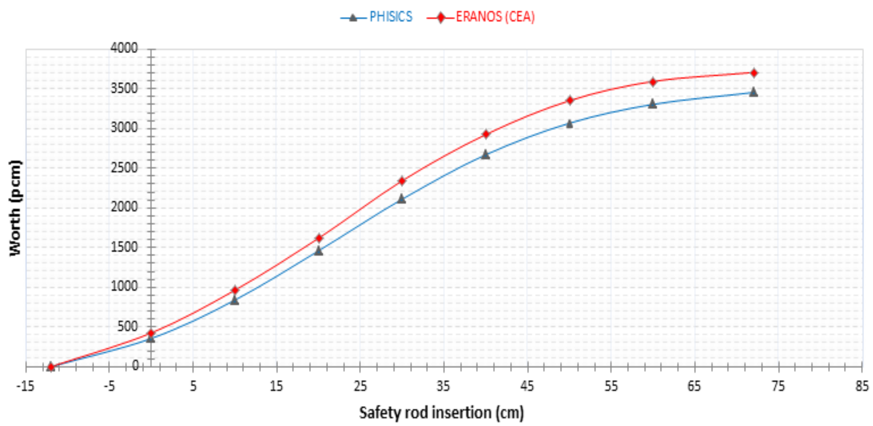


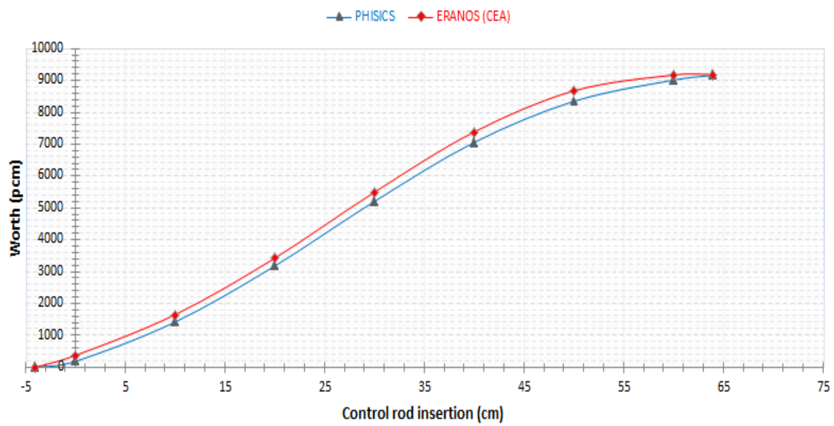
Cross Section Calculation Method

- ECCO cell/lattice code (ERANOS 2.1 package) with 33 energy groups structure (JEFF-3.1 library) and branching for tabulation
- Thermal expansion and Doppler effect evaluated



RESULTS: CR and SR Calibration Curve





- The safety rod worth calculated by CEA is 3700 pcm
- The safety rod worth calculated by PHISICS is 3454 pcm

- The control rod worth calculated by CEA is 9188 pcm
- The control rod worth calculated by PHISICS is 9164 pcm

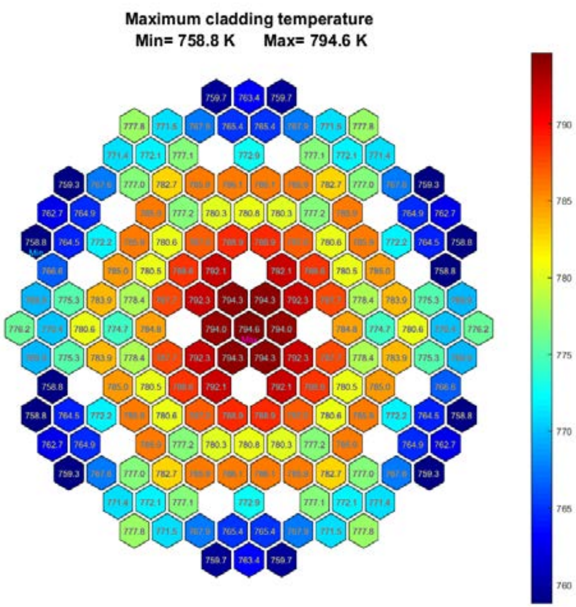
RESULTS: Nominal State at 300 MWt (1/2)

Parameter	Design value	PHISICS/RELAP5-3D result
Primary side		
Reactor power (MW)	300	300
Mass flow rate (kg/s)	25980	25525
Core inlet temperature(°C)	400	400
Core outlet temperature (°C)	480	480
SG lead inlet temperature (°C)	480	480
SG lead outlet temperature (°C)	400	400
Secondary side		
Feed water temperature (°C)	335	335
Steam outlet temperature (°C)	450	449
Steam pressure (bar)	180	180
FW mass flow rate (kg/s)	192.8	190.5

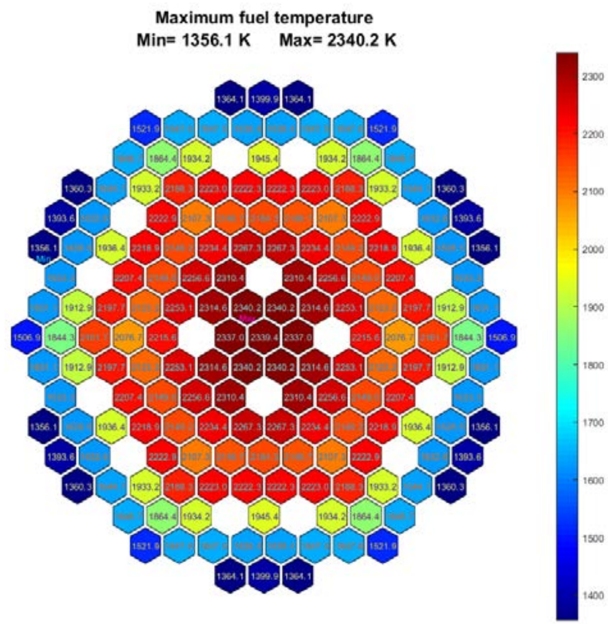
- Steady-State results are in good agreement to the design values

RESULTS: Nominal State at 300 MWt (2/2)

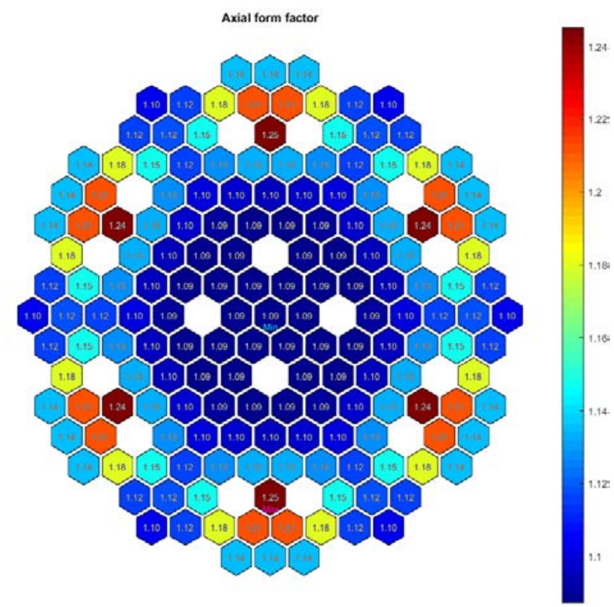
Design value (K)	823.0
Maximum cladding T(K)	794.6



Reference Value (K)	2273.0
Maximum fuel T (K)	2340.2
Deviation from RV (%)	3

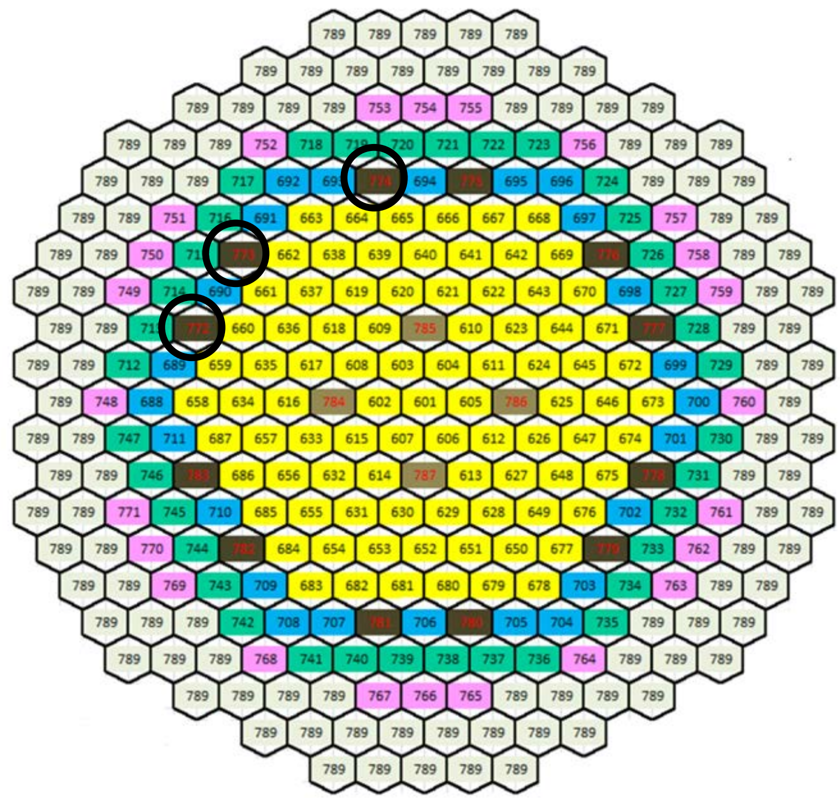


Average axial form factor	1.13

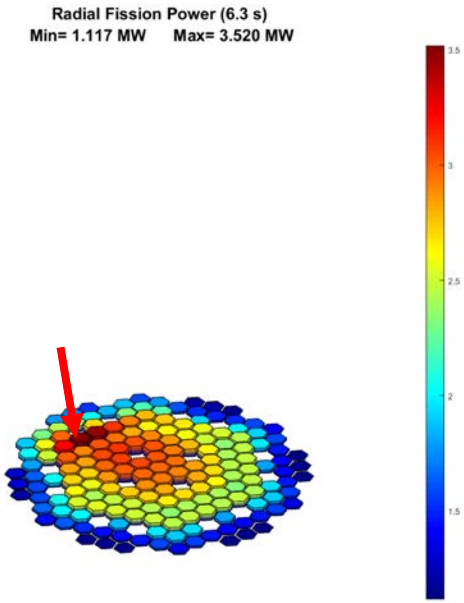


RESULTS: Rod Ejection Accident (1/2)

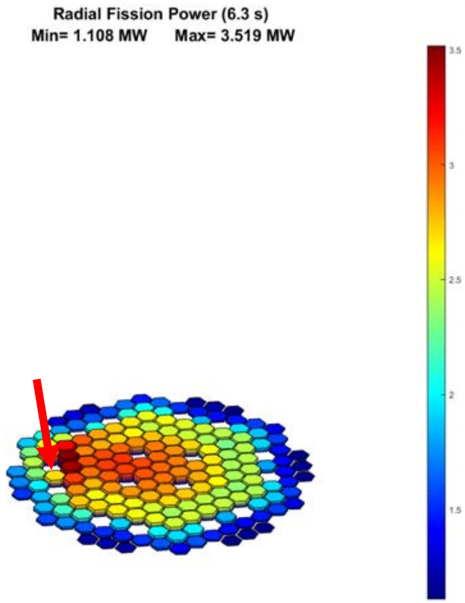
- Based on the core symmetry, the RIA (at full reactor power) has been simulated for:
  - o CR 774 (1.3$)
  - o CR 773 (1.29$)
  - o CR 772 (1.26$)
- Ejection time of 0.1 s (very conservative choice):
- TDV and TDJ used to simulate BCs
- Scram system fails after ejection



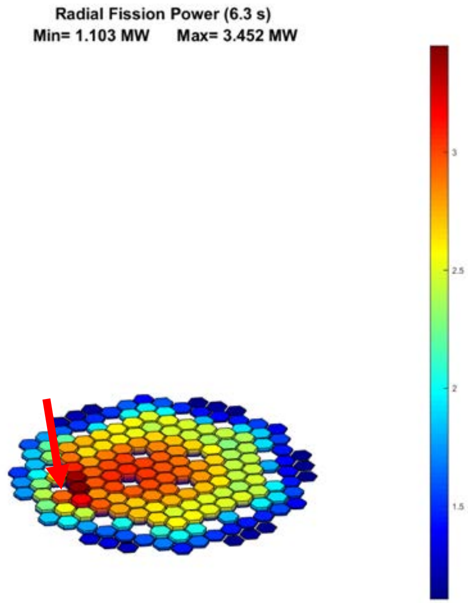
RESULTS: Rod Ejection Accident (2/2)



CR 774



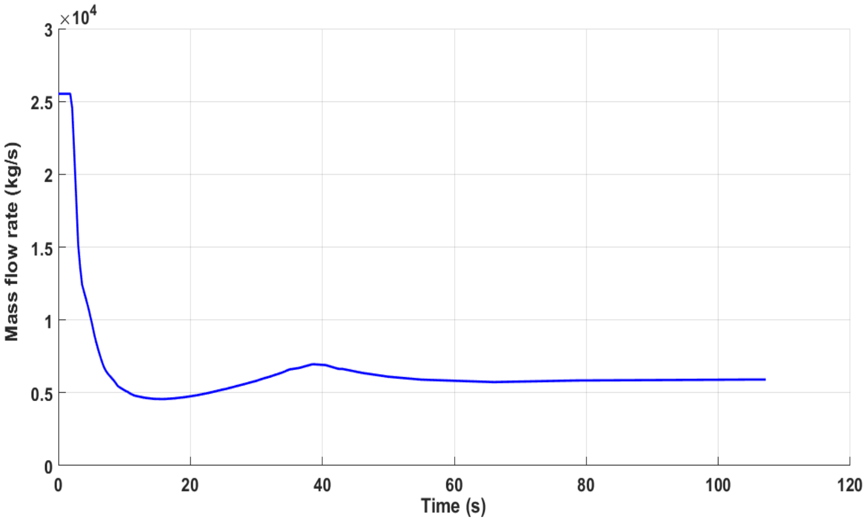
CR 773

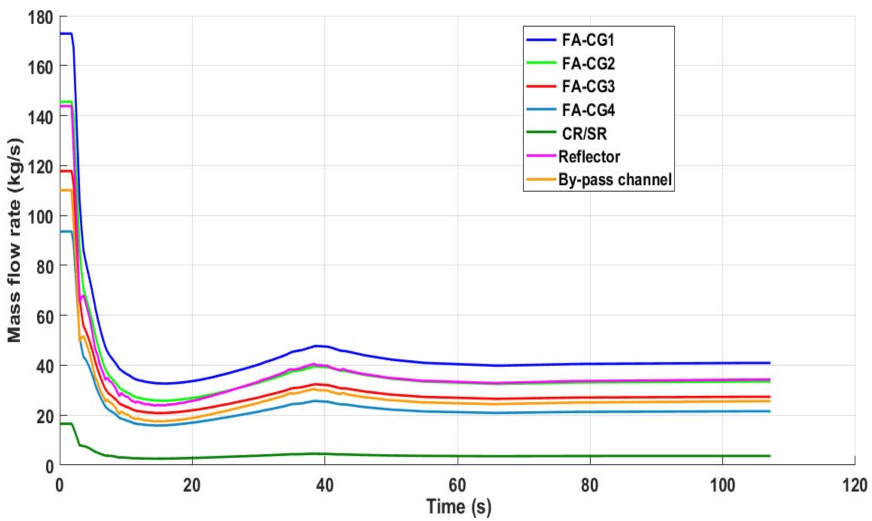


CR 772

RESULTS: ULOF transient (in backup slides)

- The Unprotected Loss of Flow transient is initiated by the loss of power supply to all primary pumps
- The reactor scram is supposed to fail and then the core power is driven by reactivity feedbacks
- The secondary system is supposed to remain in nominal conditions (no control of feed water flow rate)





Thank you

Questions?