Multi-physics Analysis of CEA Drop Accident

Sebastian Grzegorz Dzień and Aya Diab
Department of Nuclear Power Plant Engineering
KEPCO International Nuclear Graduate School

KNS Autumn Meeting 2023

Presentation Agenda

- Introduction
- Research goal
- Multi-physics approach
- Accident description
- Model description and methodology
- Results
- Conclusion

Research Goal

The goal of this research is to conduct a **multi-physics simulation** of **CEA drop accident** for APR1400 to obtain more realistic prediction of the system by using two-way internal coupling of **RELAP5/SCDAP/MOD3.4 with 3DKIN 5.2.1** and compare the results with one-way coupled conservative analysis, using point kinetics.

Multi-Physics Approach

- Beneficial for accidents with **asymmetrical core power distribution**
- **Reflects detailed 3D core modeling**, with instantaneous updates of feedback mechanisms (FTC, MTC)
- High-fidelity simulation brings **more realistic system response**
- **Higher safety margin**
- More **flexible** and **economic operation**

CEA Drop Accident Description

- Belongs to **Reactivity and Power Distribution Anomalies,** and classified as **Anticipated Operational Occurance (AOO)**
- Caused by interruption in the electrical power to the **CEDM holding coil of a single CEA**
- Rapid reactivity insertion causes **asymmetrical core power distribution,** with strong **reactivity feedback mechanisms**
- Limiting case: single CEA drop that **does not cause a reactor trip**
- Main concern: approaching the **specified acceptable fuel design limit** (SAFDL) on the **DNBR**

CEA Drop → Reduction in core power and P-T-S side power to load mismatch → RCS cooldown due to power mismatch → MTC adds positive reactivity – return to power → SAFDL approach on DNBR

Initial Conditions

Initial conditions for **conservative analysis** reported in APR1400 DCD Chapter 15, with parameters set for **worst case scenario**.

Parameter	Value
Core power level, MWt	4062.66
Core inlet coolant temperature, °C	295.0
Core mass flow rate, 10^6 kg/hr	69.64
Pressurizer pressure, kg/cm^2	152.9
Initial core minimum DNBR	1.81
Dropped CEA reactivity worth, $10^{-2}\Delta\rho$	-0.13
Doppler reactivity	Most negative
MTC, $\Delta\rho/^0C(\Delta\rho/^0F)$	-5.4×10^{-4} (-3.0×10^{-4})

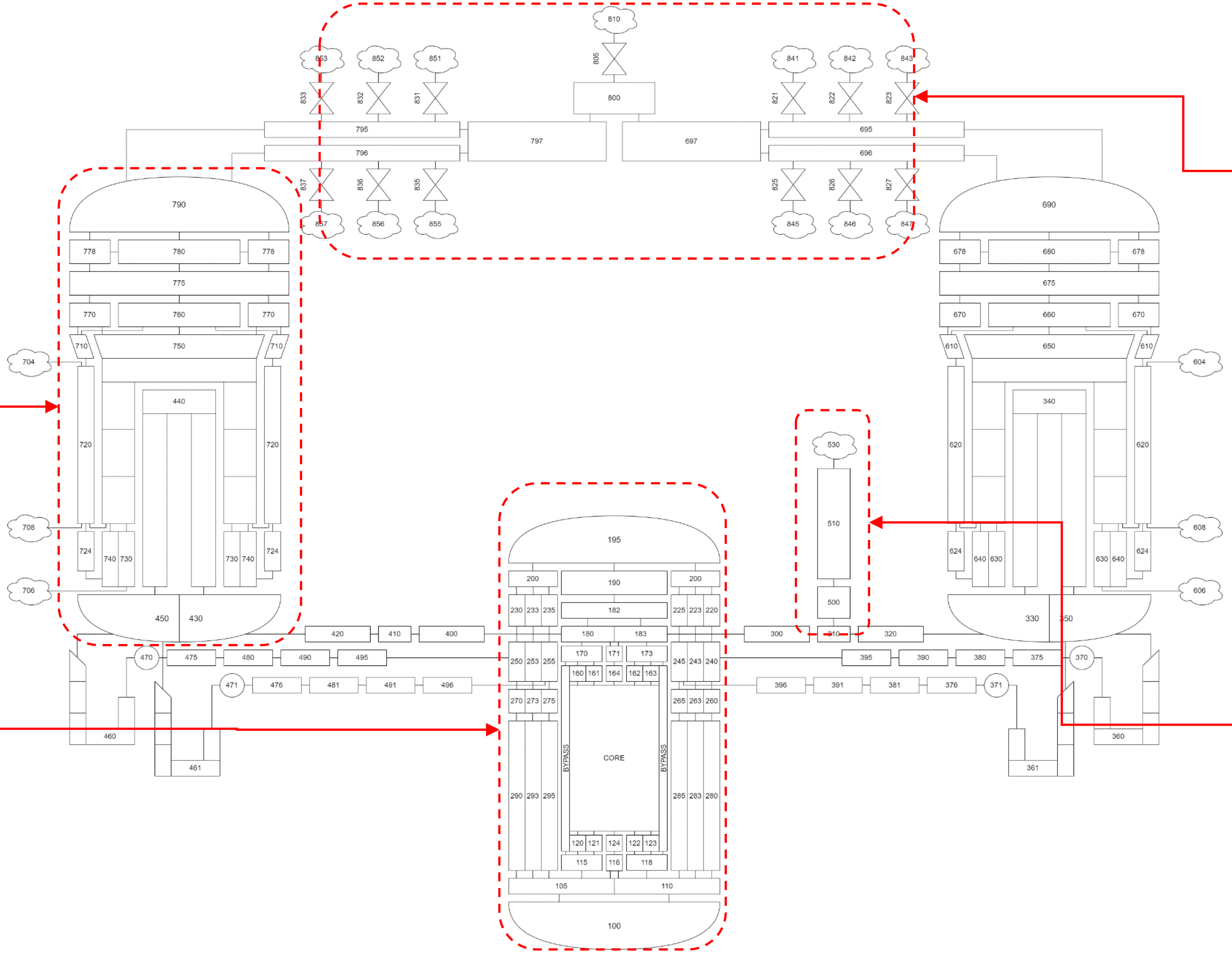
Model Description

Steam Generators (SGs)

- Two SGs - each connected to the RPV via one hot leg and two cold leg
- Heat generated on the primary side is transferred to the SGs via the u-tubes
- The u-tube section is modeled with equivalent heat transfer and pressure drop conditions
- Secondary water is provided by the Main Feedwater System (MFWS) as boundary condition
- Steam generated in the SGs is directed via the main steam line to the turbine modeled as a boundary condition
- Other important components of the SGs are: evaporator, separator, dryer, dome

Reactor Pressure Vessel (RPV)

- The core is represented using an average and a hot channel, surrounded by an annular core shroud together with the core bypass
- The core connects to an upper plenum and a lower plenum
- Two hot legs lead the coolant from the RPV to the SGs u-tubes, four cold legs connect the RCPs to the downcomer
- The downcomer is modeled using annulus six components



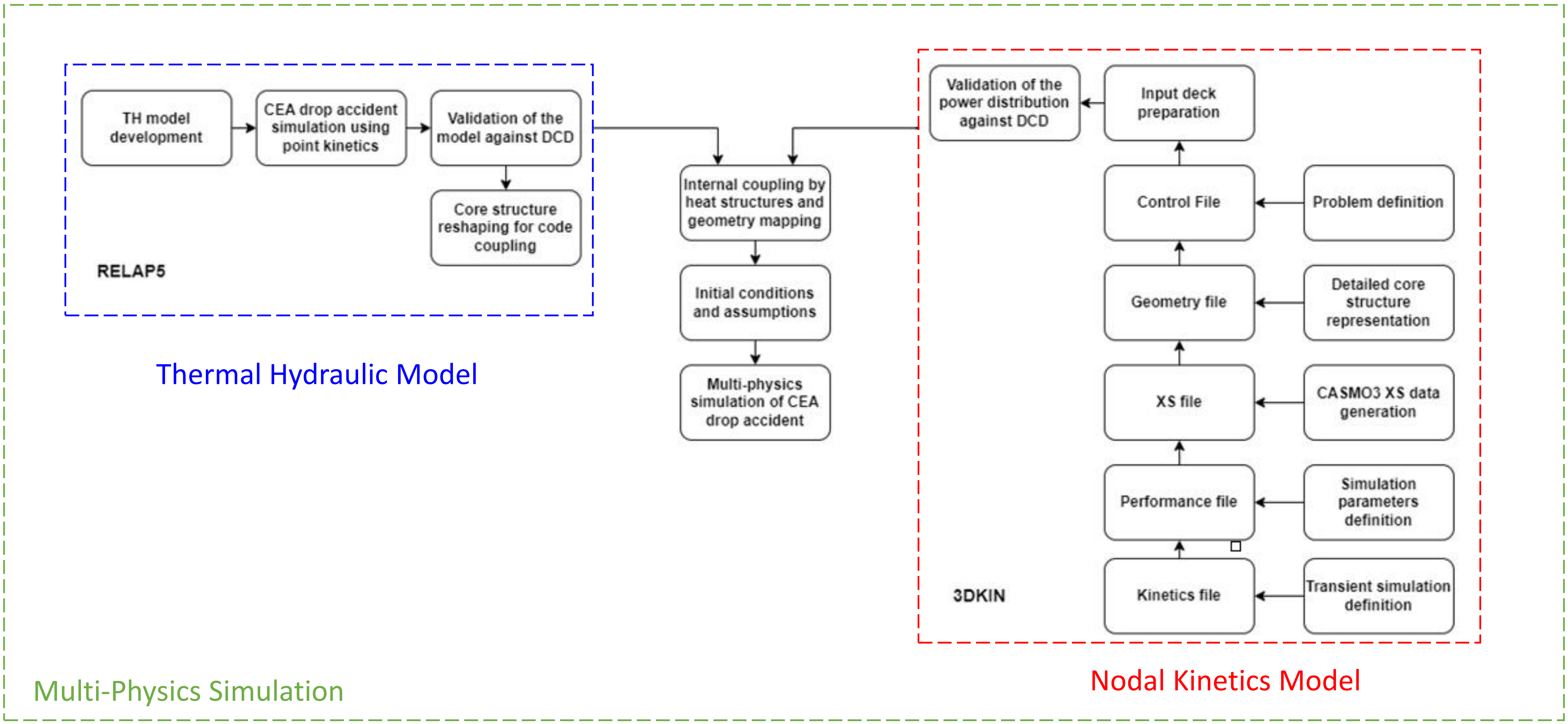
Main Steam System (MSS)

- The Main Steam System (MSS) has four main steam lines leading from the two SGs to a common header, and then to the turbine through an isolation valve.
- Each line is connected to a set of Main Steam Safety Valves (MSSVs) to protect the system against over-pressurization.

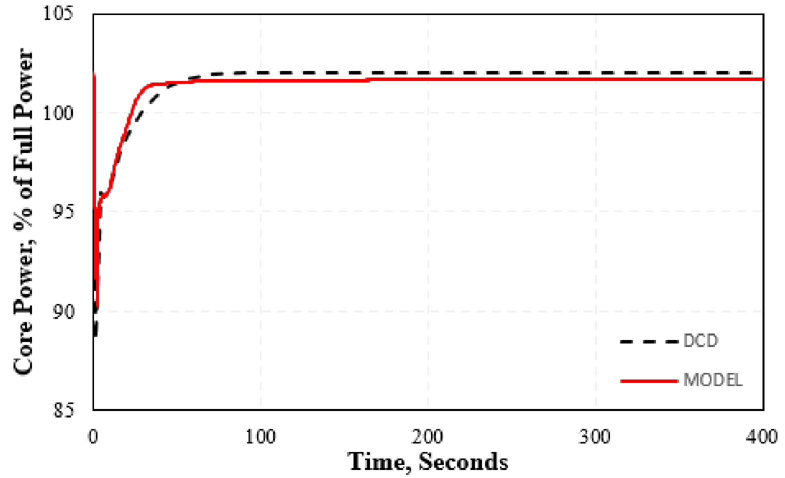
Pressurizer (PZR)

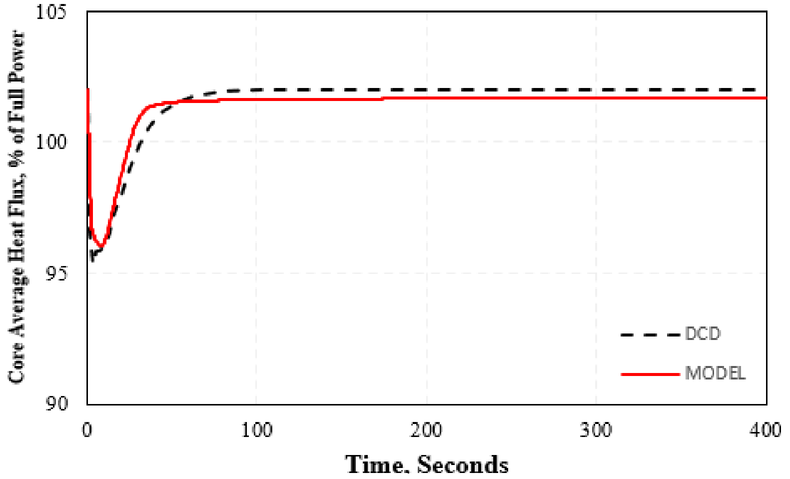
- Maintains operational pressure in the primary system loop.
- In steady-state, the pressurizer pressure is imposed by a boundary condition. In transient, the pressure is determined by the system conditions and Pilot-Operated Safety Relief Valves (POSRVs) operation.

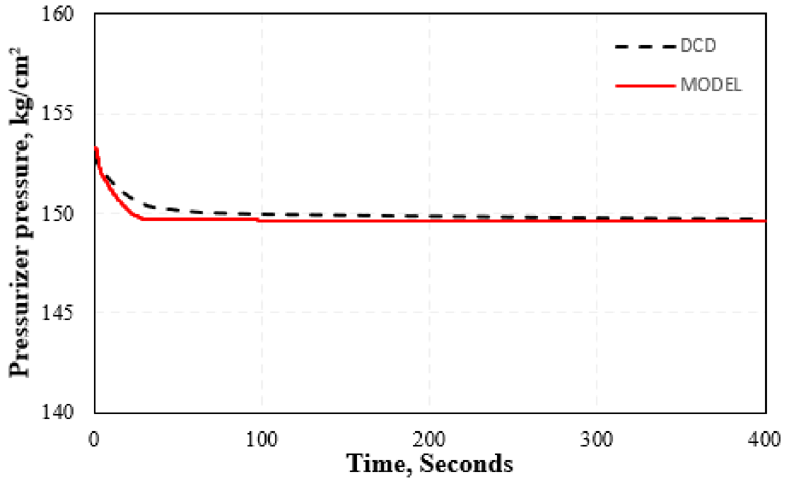
Methodology Overview

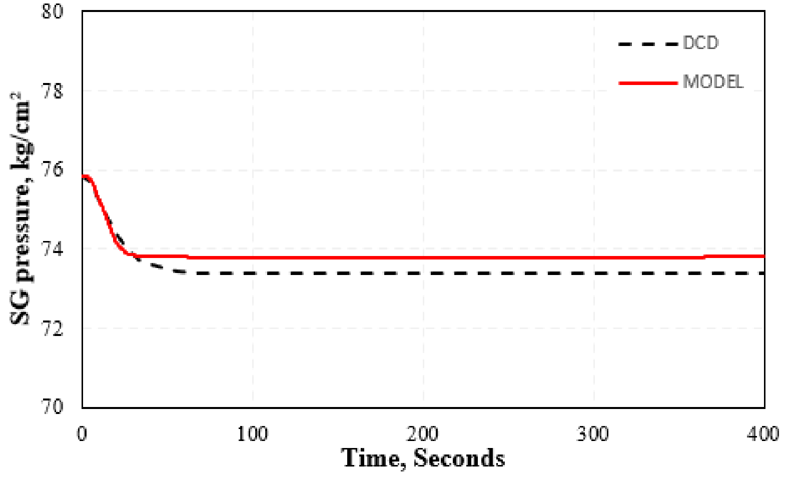


TH Model Validation



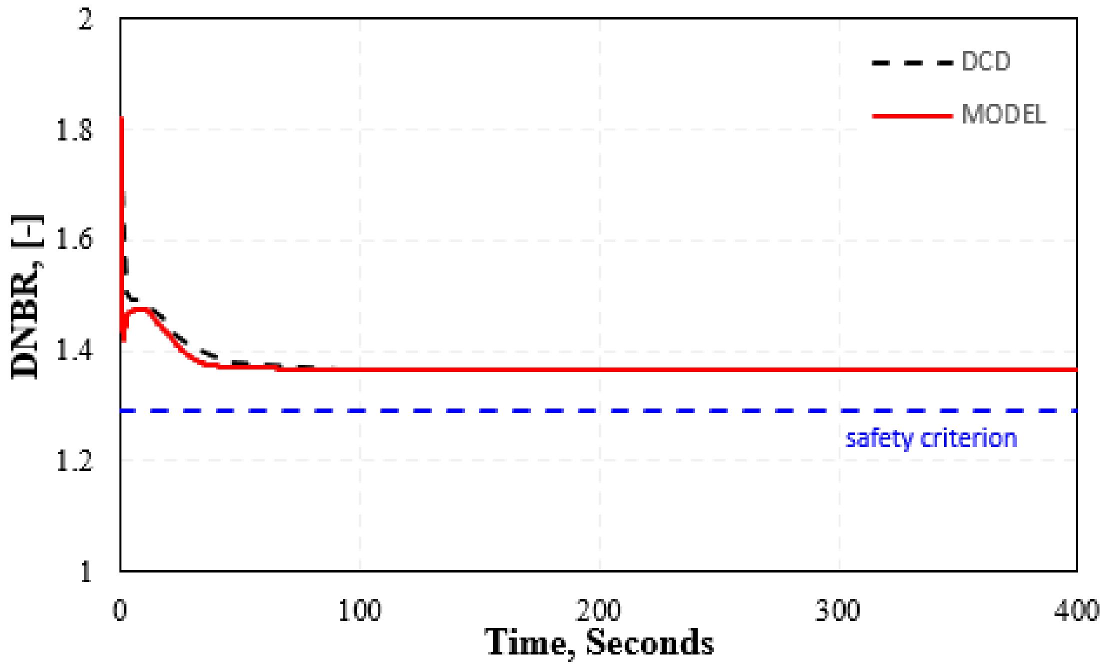






TH Model Validation

- DNBR calculated for **hot channel**
- **W-3 correlation** is used
- Minimum DNBR value is **higher than the safety criterion** of 1.29

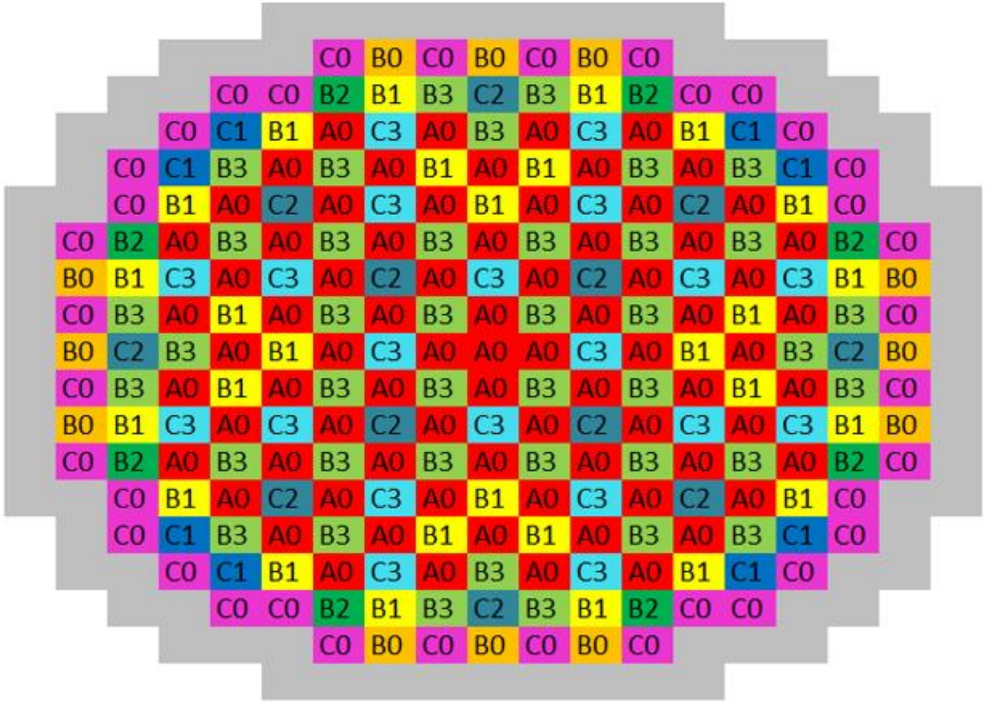


Time (sec)	Event	DCD	Model
0.0	A single CEA begins to drop	-	-
0.0	Max. PZR pressure, kg/cm^2A	152.9	153.1
382.5	Minimum DNBR	1.36	1.3645

KINGS

APR1400 Core Model

- **241 fuel assemblies** (FA)
- **9 groups of FAs**, based on enrichment, burnable absorber rods etc.

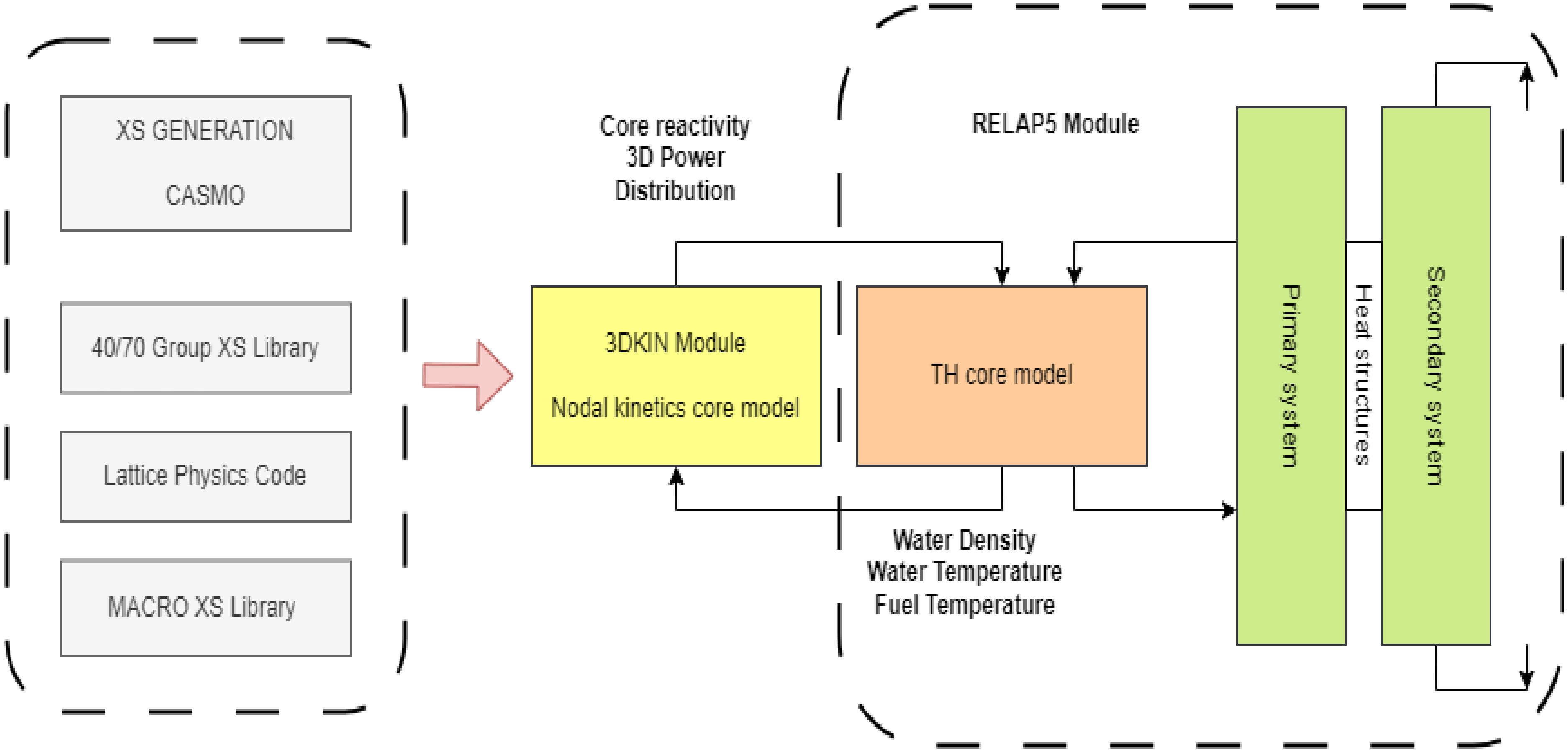


Assembly Type	Number of Fuel Assemblies	Fuel Rod Enrichment (w/o)	No. of Rods Per Assembly	No. of Gd_2O_3 Rods per Assembly	Gd_2O_3 Contents (w/o)
A0	77	1.71	236	-	-
B0	12	3.14	236	-	-
B1	28	3.14/2.64	172/52	12	8
B2	8	3.14/2.64	124/100	12	8
B3	40	3.14/2.64	168/52	16	8
C0	36	3.64/3.14	184/52	-	-
C1	8	3.64/3.14	172/52	12	8
C2	12	3.64/3.14	168/52	16	8
C3	20	3.64/3.14	120/100	16	8

Cross-Section Library

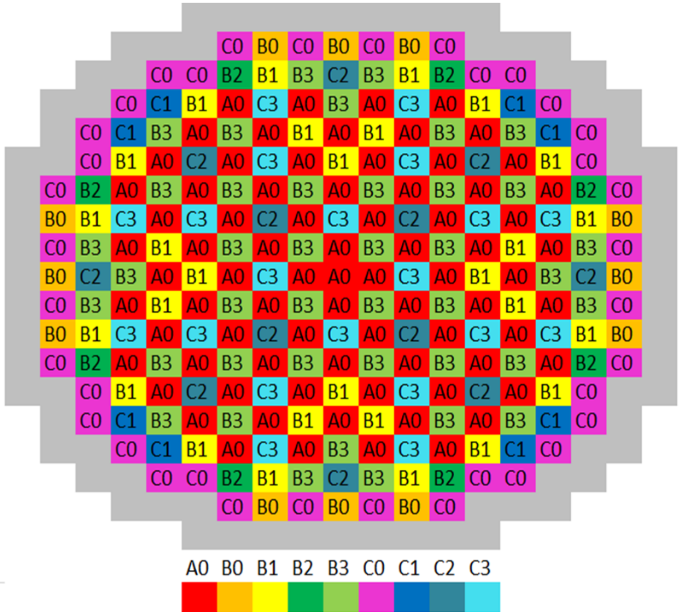
- Proper modeling of each group of FAs requires details such as **macroscopic transport, absorption, fission and scattering cross-sections for two energy groups** to be provided to the 3DKIN
- **CASMO3 lattice code** was used to generate those parameters
- **CEAs movements, MTC and Doppler reactivity** are reflected

Two-Way Implicit Code Coupling

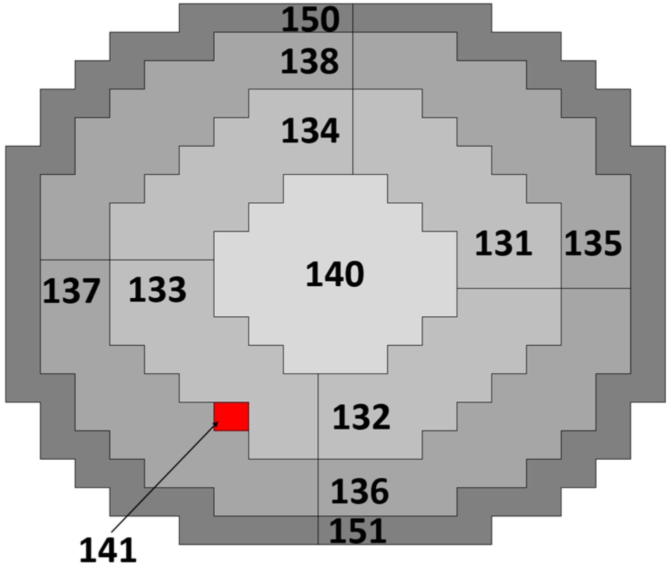


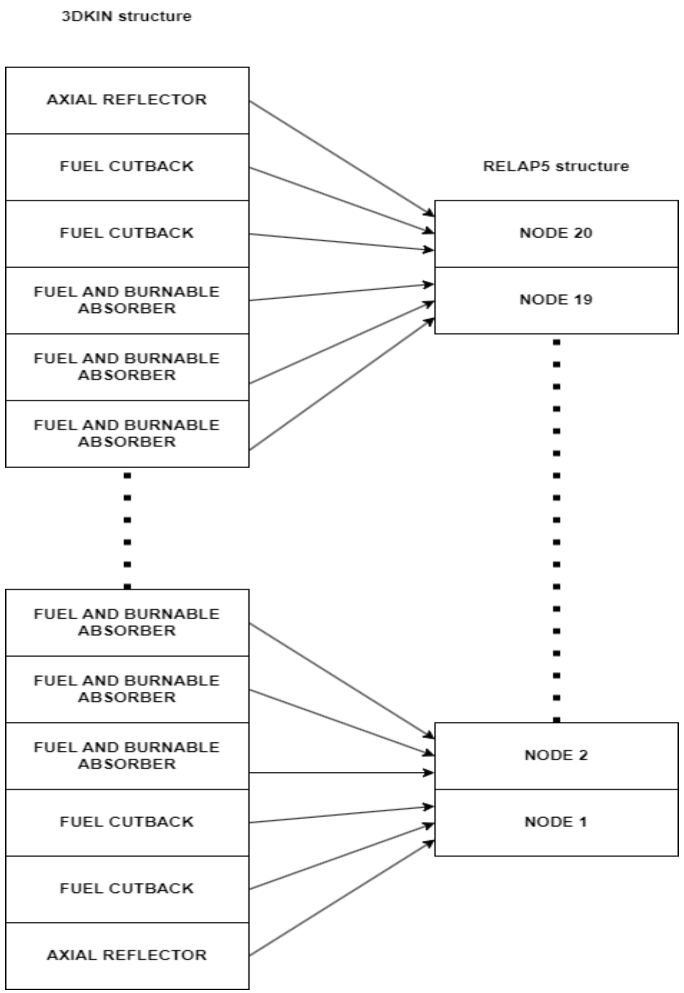
Core Model Mapping

3DKIN core model (assembly level)



RELAP5 nodes



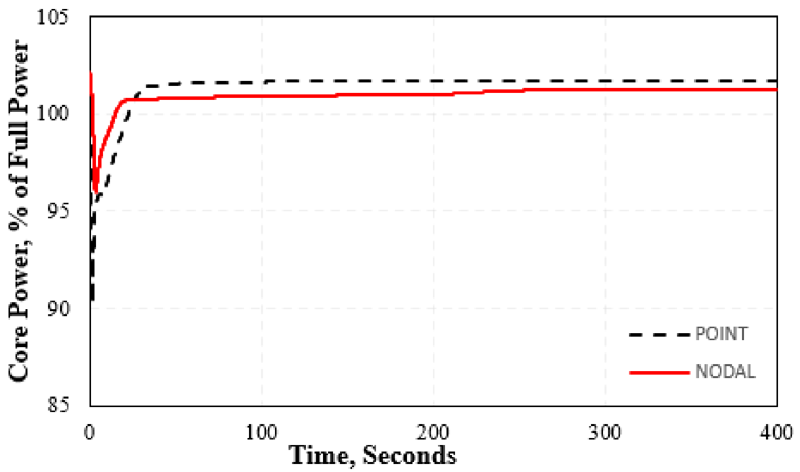


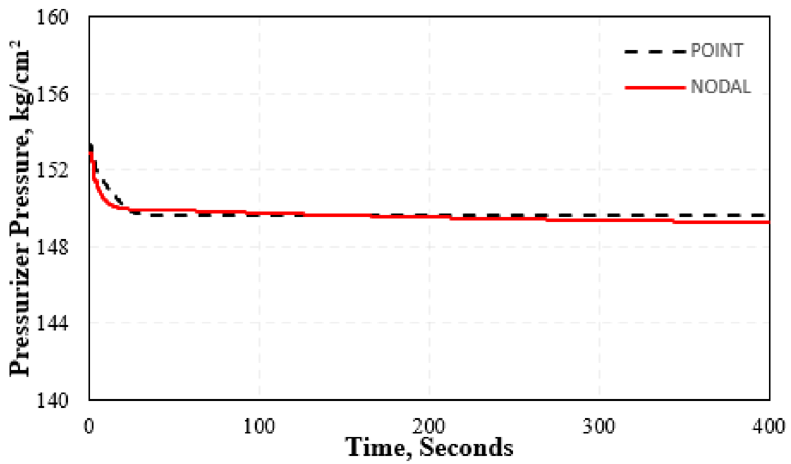
3DKIN NK Model Validation

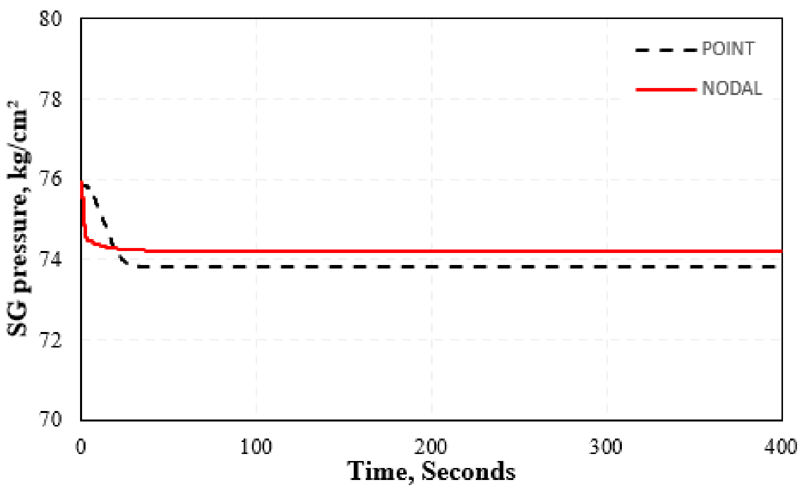
Parameter	DCD	Model
Core power, MWt	3983.0	3983.0
Core inlet temp, ⁰C	295.0	291.5
Core mass flow rate, 10^6 kg/hr	75.6	76.7
Pressurizer pressure, kg/cm^2	158.2	158.2
SG pressure, kg/cm^2	68.9	69.06
Core outlet temp, ⁰C	323.9	320.68

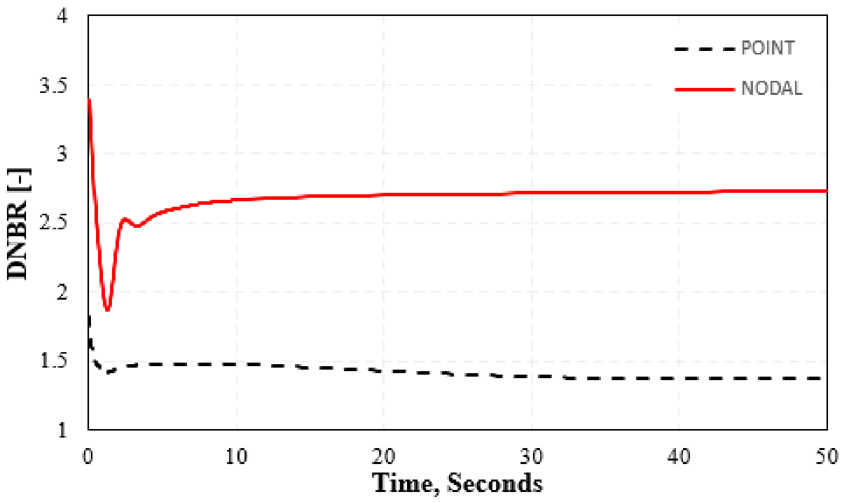
5.5	5.8	5.5	4.3	5.4	0.9	2.6	0.7	1.8	2.7
4.9	5.5	4.9	4.8	3.5	2.8	0.1	0.8	1.4	2.2
4.8	4.3	4.8	4.1	2.4	0.1	1.2	1.9	1.8	1.6
3.5	5.4	3.5	2.4	0.2	1.4	1.0	1.0	2.7	
2.8	0.9	2.8	0.1	1.4	2.6	2.0	5.5	4.6	
0.1	2.6	0.1	1.2	1.0	2.0	5.5	6.1	3.7	
0.8	0.7	0.8	1.9	1.0	5.5	6.1	3.9		
1.4	1.8	1.4	1.8	2.7	4.5	3.7			
2.2	2.7	2.2	1.6						

Multi-Physics Simulation Results



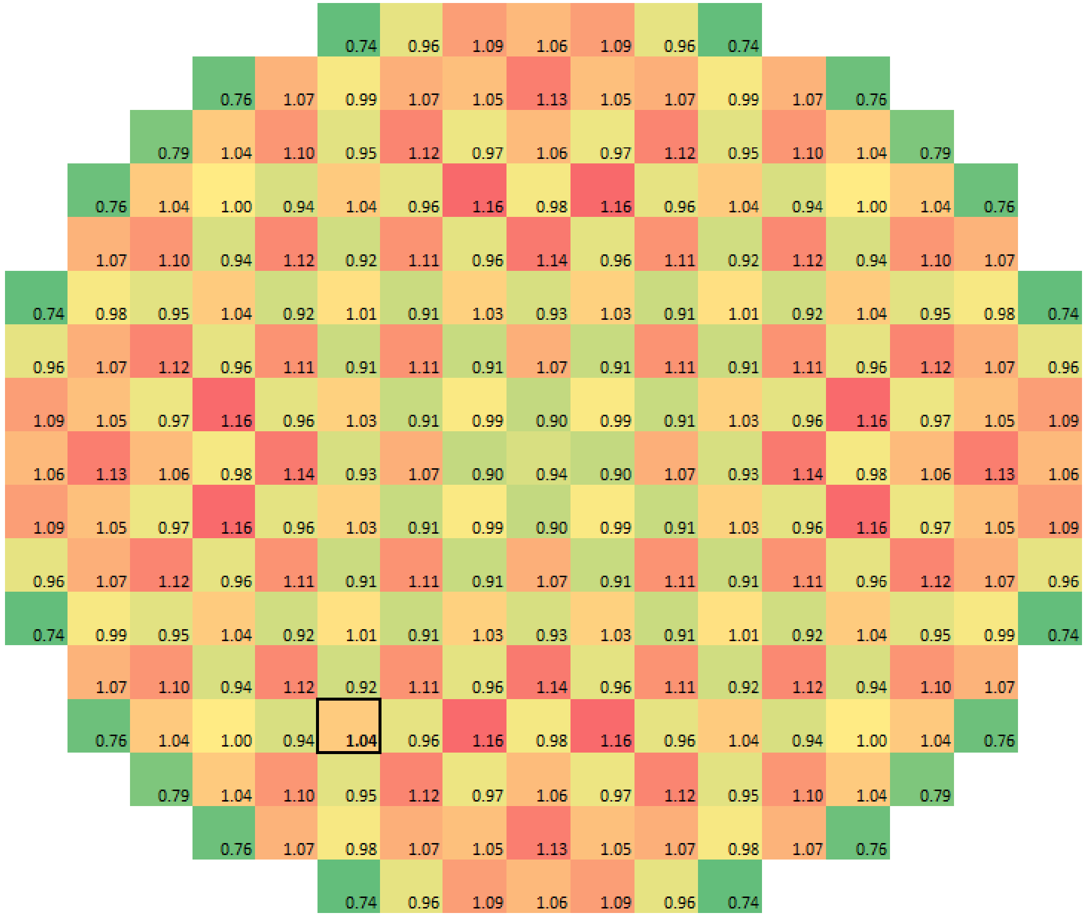




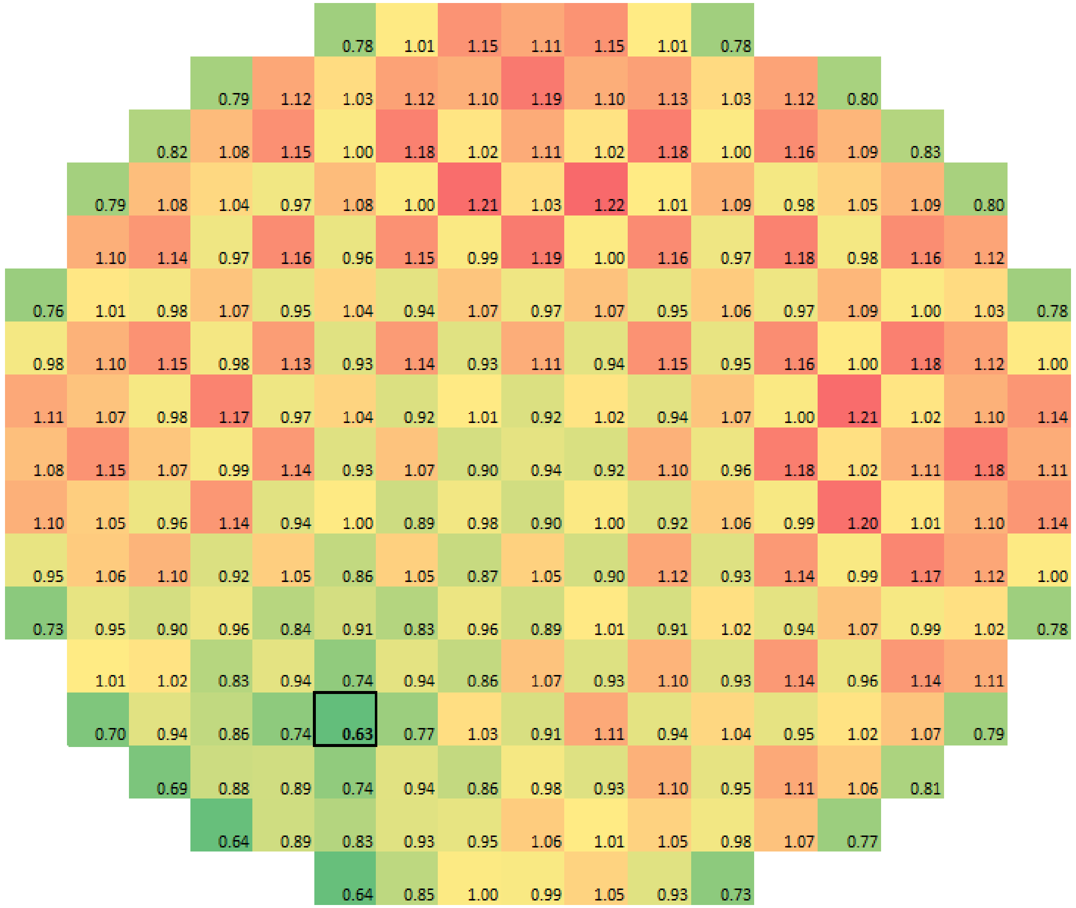


KINGS

Core Power Distribution



Beginning of Transient, t = 0 sec



End of Transient , t = 400 sec

Conclusion

- **More realistic results** have been achieved by using two-way code coupling of RELAP5/SCDAP/MOD3.4 with 3DKIN
- Multi-physics analysis shown **asymmetrical character of this accident**, which is not represented in point kinetics model
- Simulation provides a **larger safety margin**, hence more operational flexibility can be achieved

Acknowledgement

This research was supported by the 2023 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.

Special appreciation is due to F&C Technology for their valuable advice with this project during the internship

Thank you for your attention

감사합니다