Development of BEPU Methodology using Multi-Physics Coupling Code based on RAST-K

UNIST CORE Lab.

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KNS2023S

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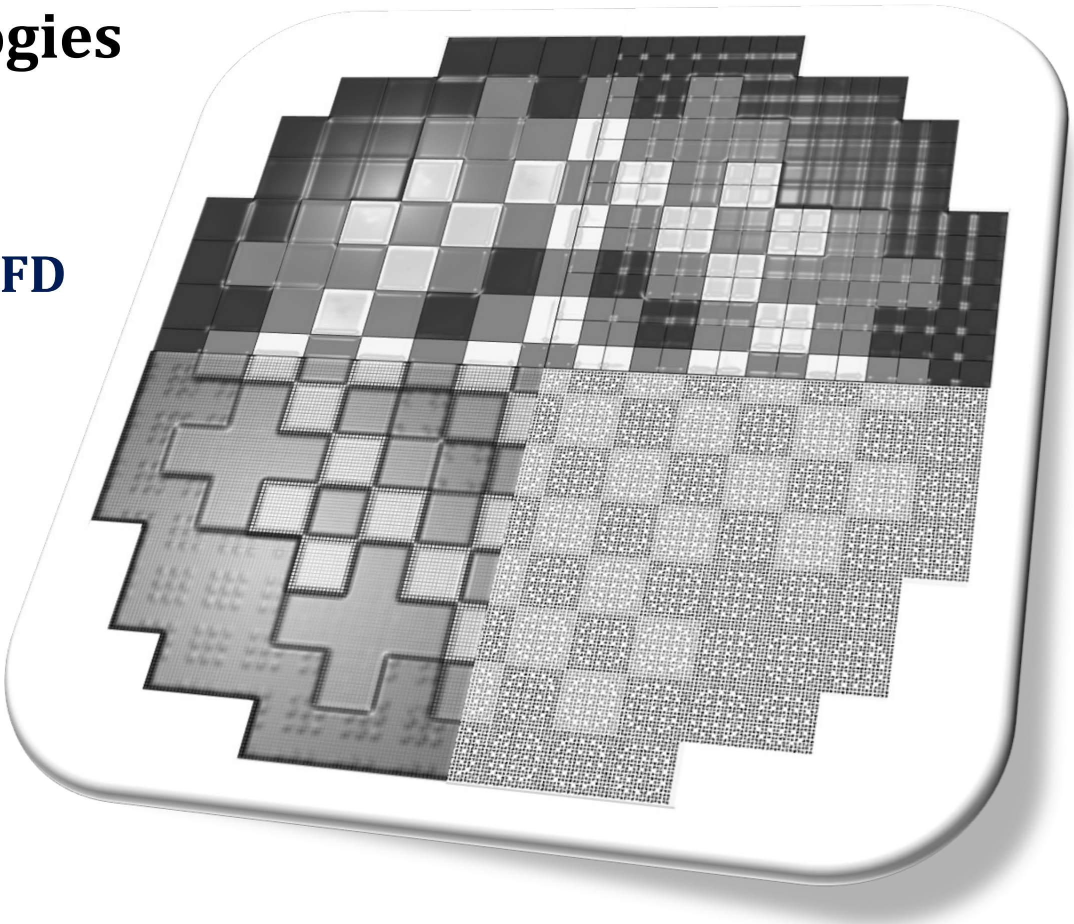
Contents

1. Introduction

Development of BEPU Methodology using Multi Physics coupling code based on RAST-K

Introduction

- **Nodal Diffusion Code RAST-K v2**
  - Developed by UNIST since 2017
  - Funded by KHNP-CRI
- **Features and methodologies**
  - XS generation: STREAM
  - XS functionalize
  - Nodal solver: MG UNM + CMFD
  - Pin-by-pin kernel
  - 1-D channel TH solver
  - Micro depletion with CRAM
  - Core design & analysis
- **Application**
  - Practical PWR design
  - V&V for PWR in Korea
  - Multi-physics coupling



Introduction

- **Application of RAST-K**

RAST-K

Reactor core design
- *SMR*
- *ATF core*

Safety analysis
- *REA*
- *MSLB*

ML
- *Optimization*
- *Classification*
- *Regression*

Reactor core analysis
- *OPR1000*
- *APR1400*
- *WH*
- *CPI*

Platform
- *enuSpace*
- *PI interface*

SNF
- *AutoCASK*
- *Source-term*

Multi-physics
- *CTF*
- *FRAPCON/TRAN*
- *FOREST*
- *VIPRE/BOA*
- *MARS*
- *CUPID*

Introduction

▪ Necessity of Multi-Physics Coupling

- **Independent development of reactor analysis code in each physics area**
  - Ex.) power history from Neutronics → TH and safety analysis
    → Fuel performance analysis
- **Advantage of one-way coupling**
  - Easy to use
  - Code maintenance
  - Obtain conservatism
- **Disadvantage of one-way coupling**
  - Accumulation of conservatism
- **Strengthening of safety-related regulation**
  - Increase of demand for high-fidelity solution excluding conservatism

Introduction

- **Simplified TH module**
  - **1D heat convection of coolant**
    - Fixed pressure during steady state (negligible pressure drop)
      - Solve only mass continuity and energy conservation
      - Evaluation of water properties at single pressure
    - Closed channel
      - Parallel 1D channel / No cross-flow
    - Core exit water condition remains sub-cooled
      - Dittus-Boelter heat regime / Single-phase formulation
  - **1D heat conduction in fuel**
    - Heat produced in pellet is deposited in the coolant
      - No heat conduction in axial direction
    - Ignore TCD effect / Constant gap conductance
- **Accuracy of simplified TH module for transient?**
  - **Two-phase? Heat regime? Cross-flow?**
  - **Pellet-to-cladding interaction? Dynamic gap conductance?**

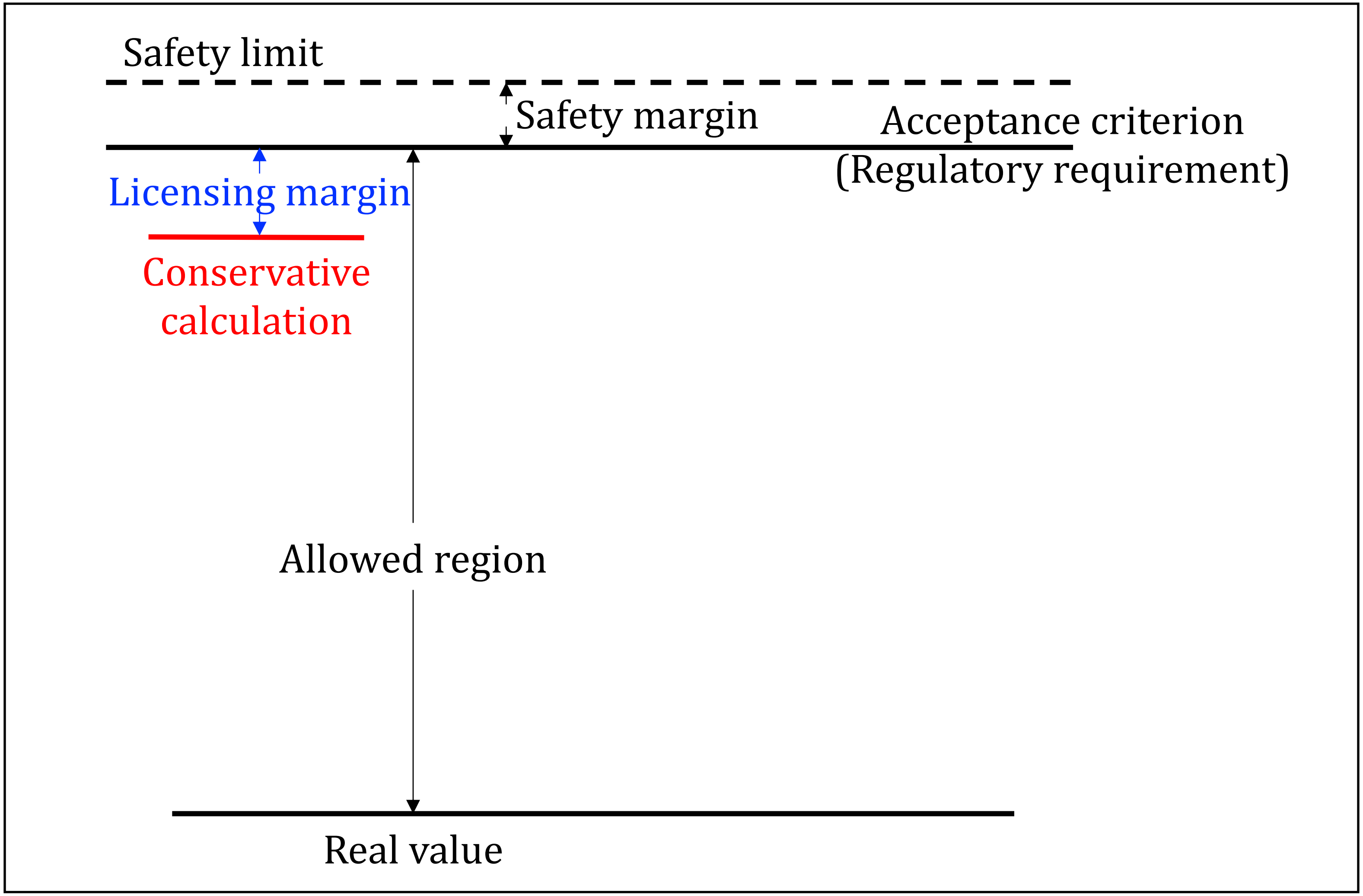
Introduction

▪ Objective of BEPU Approach

- **Demand of best-estimate solution**
  - Pessimistic hypothesis provides excessive conservatism
  - Impossible to satisfy enforced safety regulation
- **UQSA**
  - Accuracy and its confidence level obtained simultaneously
- **Source of uncertainty**
  - Modeling and simulation
    - Geometry (manufacturing)
    - Material property, ...
    - Model (including physical and mechanical properties)
  - Nuclear data
    - Cross-section
    - Covariance matrix
- **Stochastic sampling**
  - Statistical process

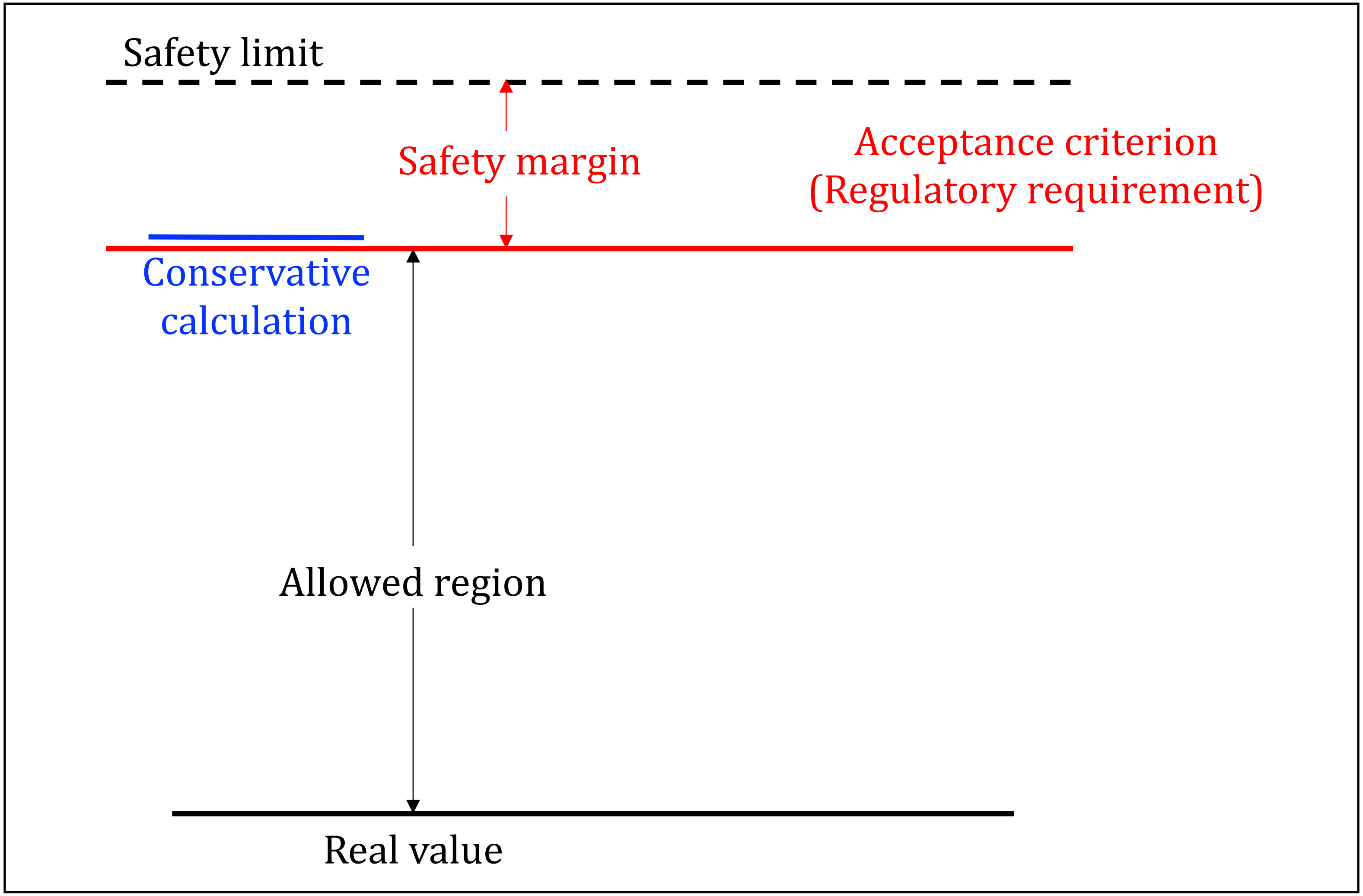
Introduction

- **BEPU approach vs. Conservative approach**
  - **1) Conservative approach**

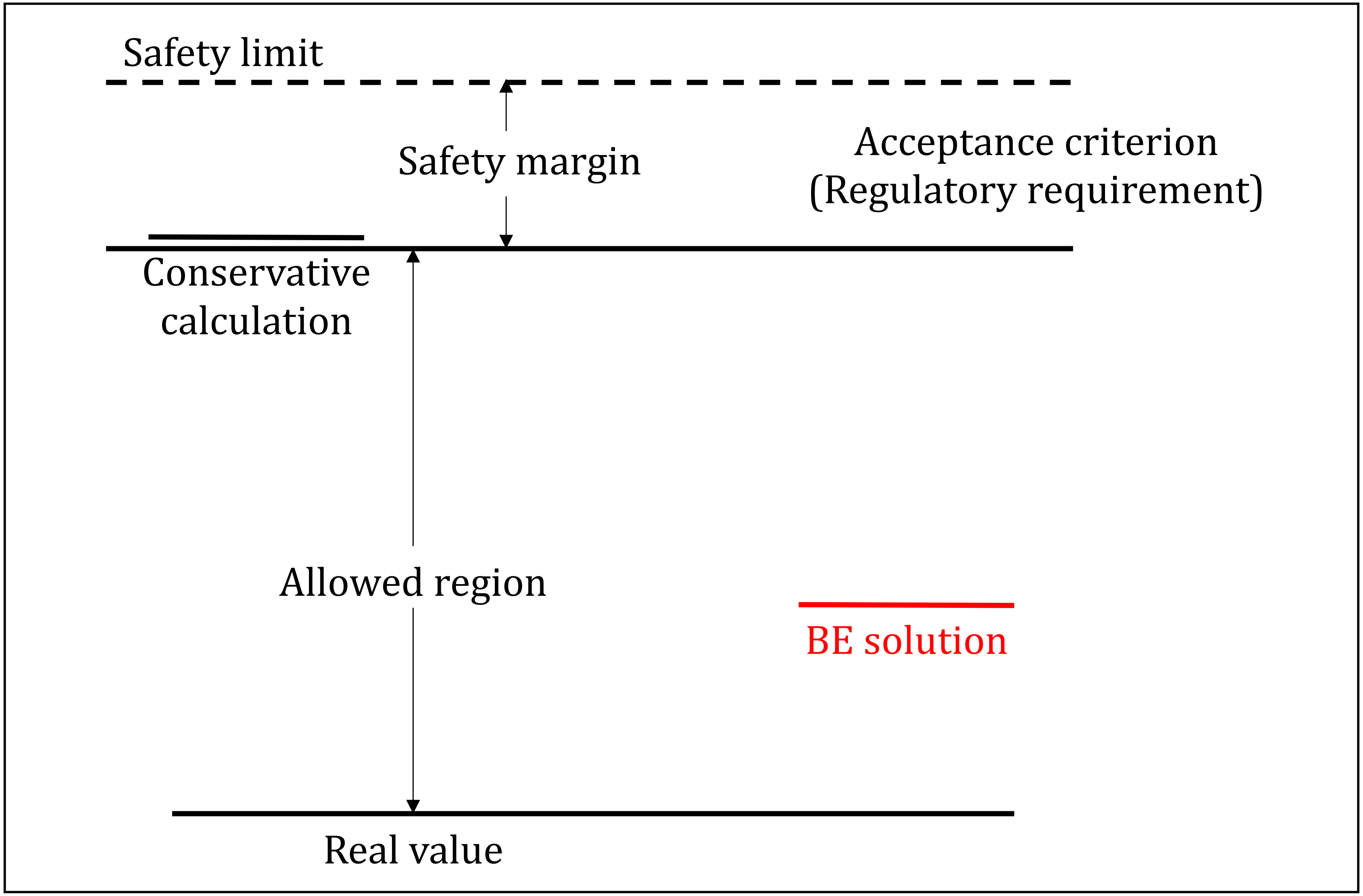


Introduction

- **BEPU approach vs. Conservative approach**
  - **2) Strengthen acceptance criterion**

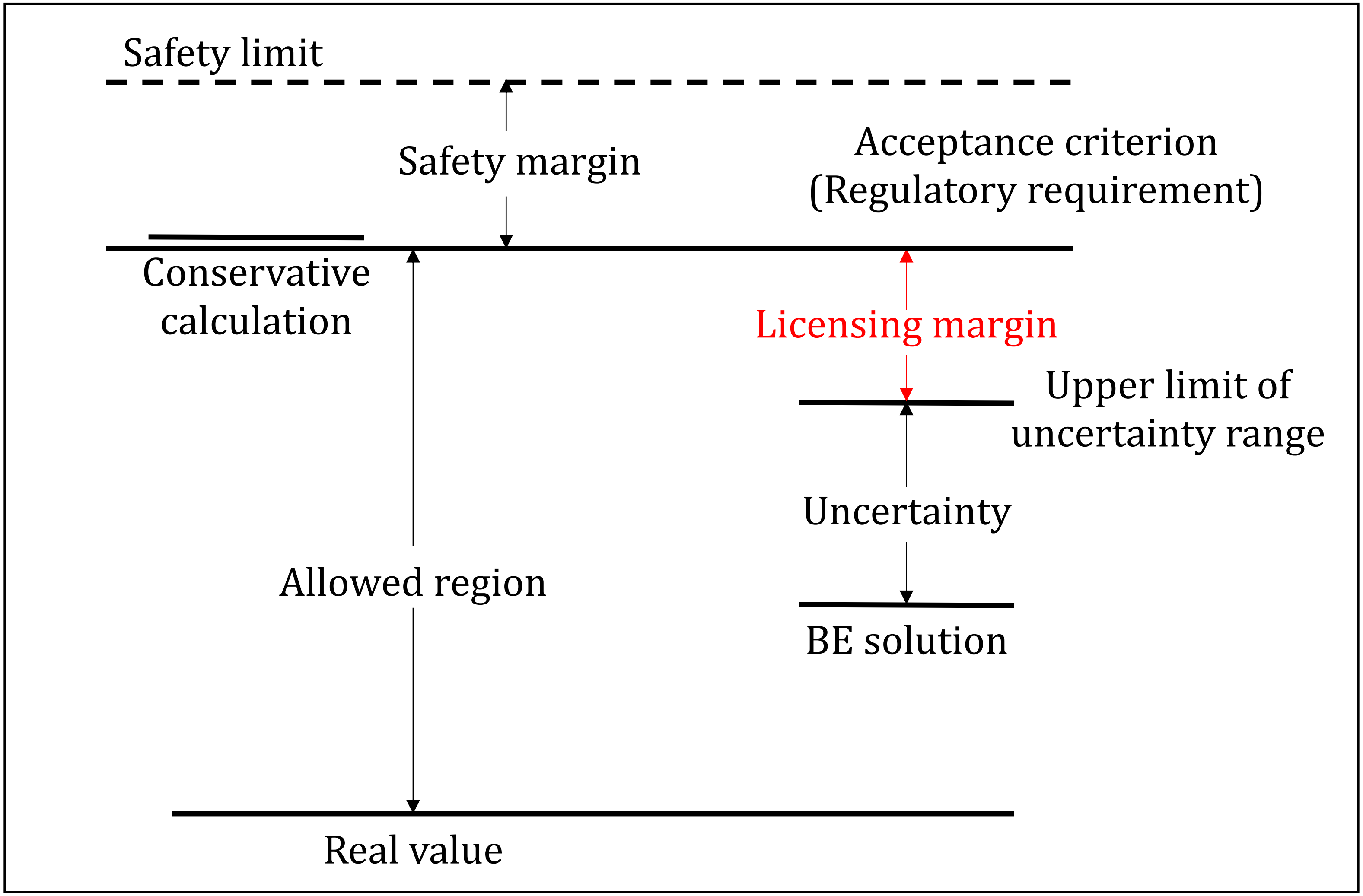


- **BEPU approach vs. Conservative approach**
  - **3) Necessity of BE solution**



Introduction

- **BEPU approach vs. Conservative approach**
  - **4) Achieve more margin even with BE solution + Uncertainty**



2. MP Coupling based on RAST-K

Development of BEPU Methodology using Multi Physics coupling code based on RAST-K

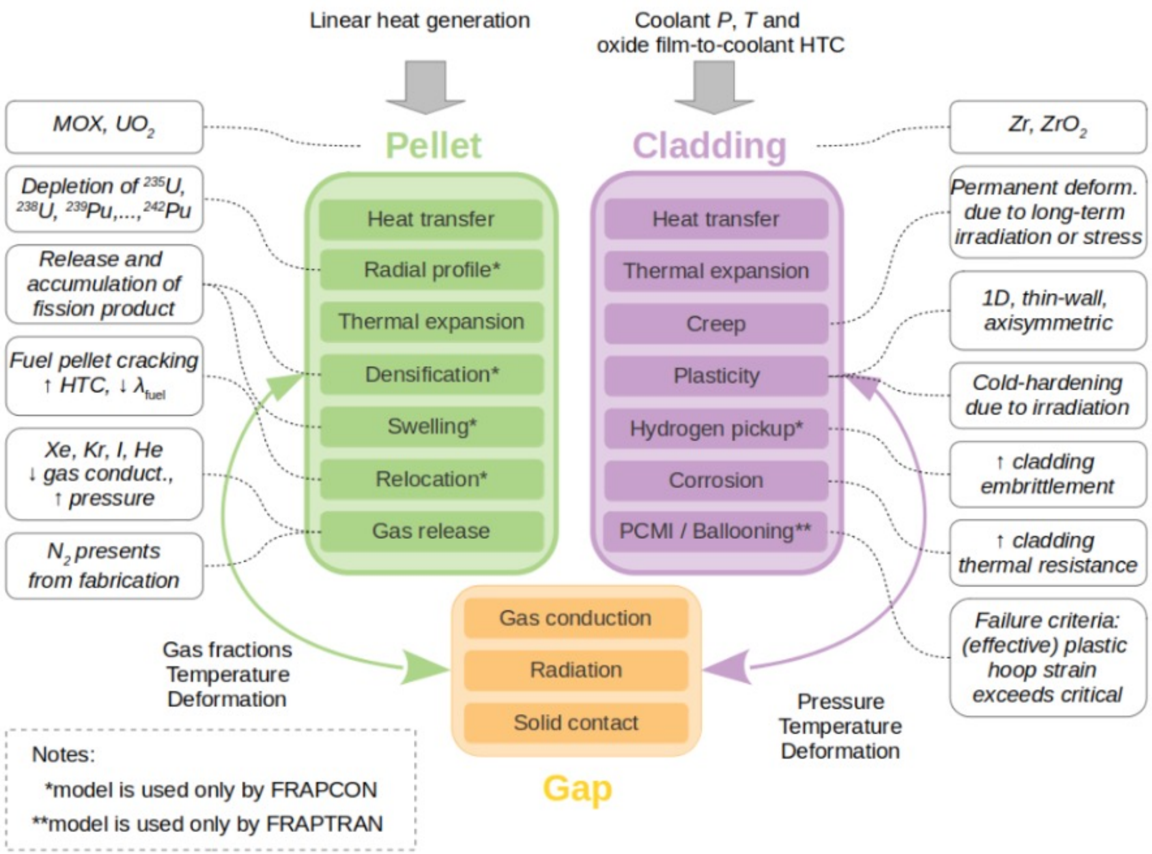
Summary of Coupled Codes

- **CTF**
  - **For LWR modeling, subchannel, two-phase, ...**
  - **Provide CTF_Coupling_Interface module**

	Internal TH solver	**CTF**
Calculation unit	Equivalent pin (node-wise)	Pin-wise (subchannel)
Two-phase	No	Yes
No. of conservation equation	1	8
Cross-flow	No	Yes
Boron tracking	No	Yes
CHF & DNBR	Yes (limited W-3)	Yes
Burnup dependent material property	No	No
Fuel mechanical model	No	No
Computational time	Low	High (~5 hours)
Memory	Low	High (2.7GB)

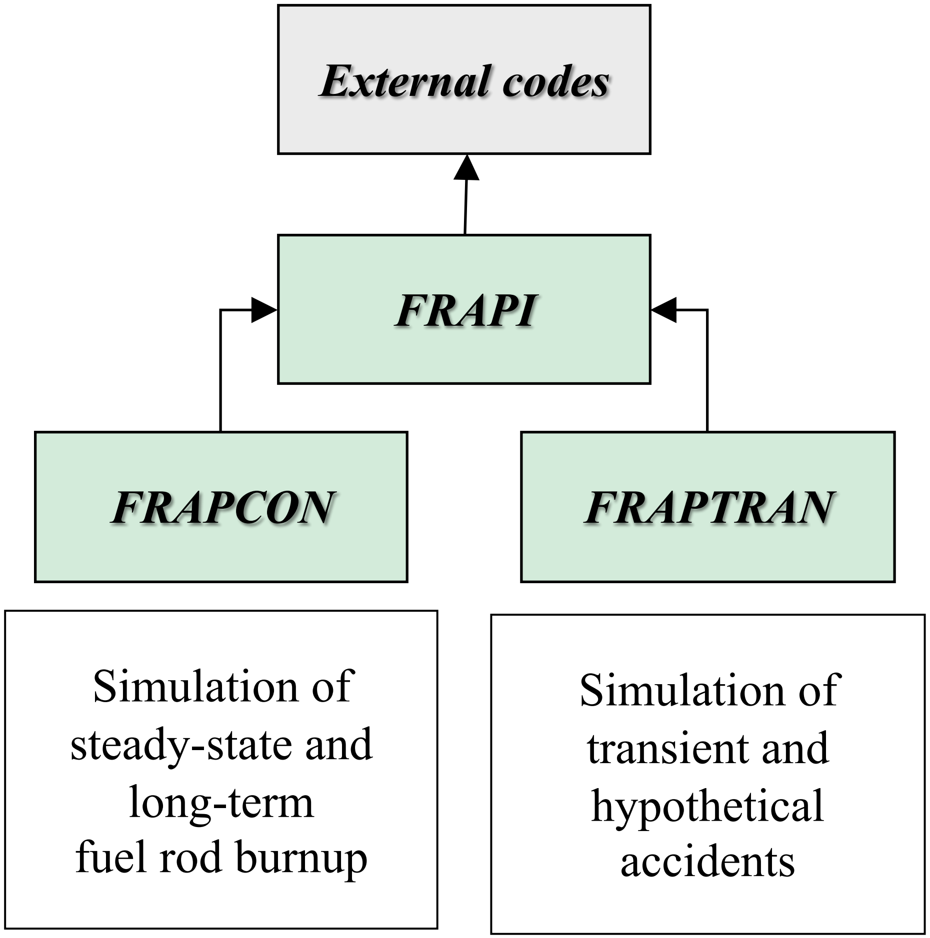
Summary of Coupled Codes

- **FRAPCON & FRAPTRAN**
  - **LWR fuel rod**
  - **Pellet-to-cladding heat transfer, mechanical deformation, pellet-to-cladding mechanical interaction, elastic-plastic deformation, fission gas release, cladding oxidation, hydrogen pickup, burnup, …**



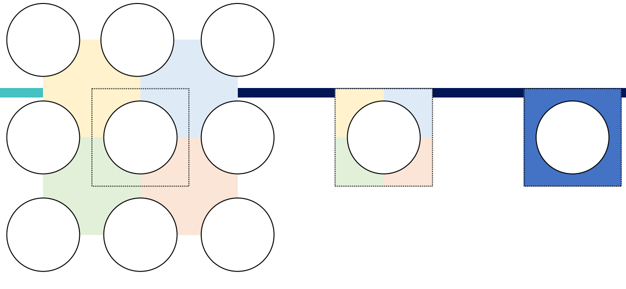
Summary of Coupled Codes

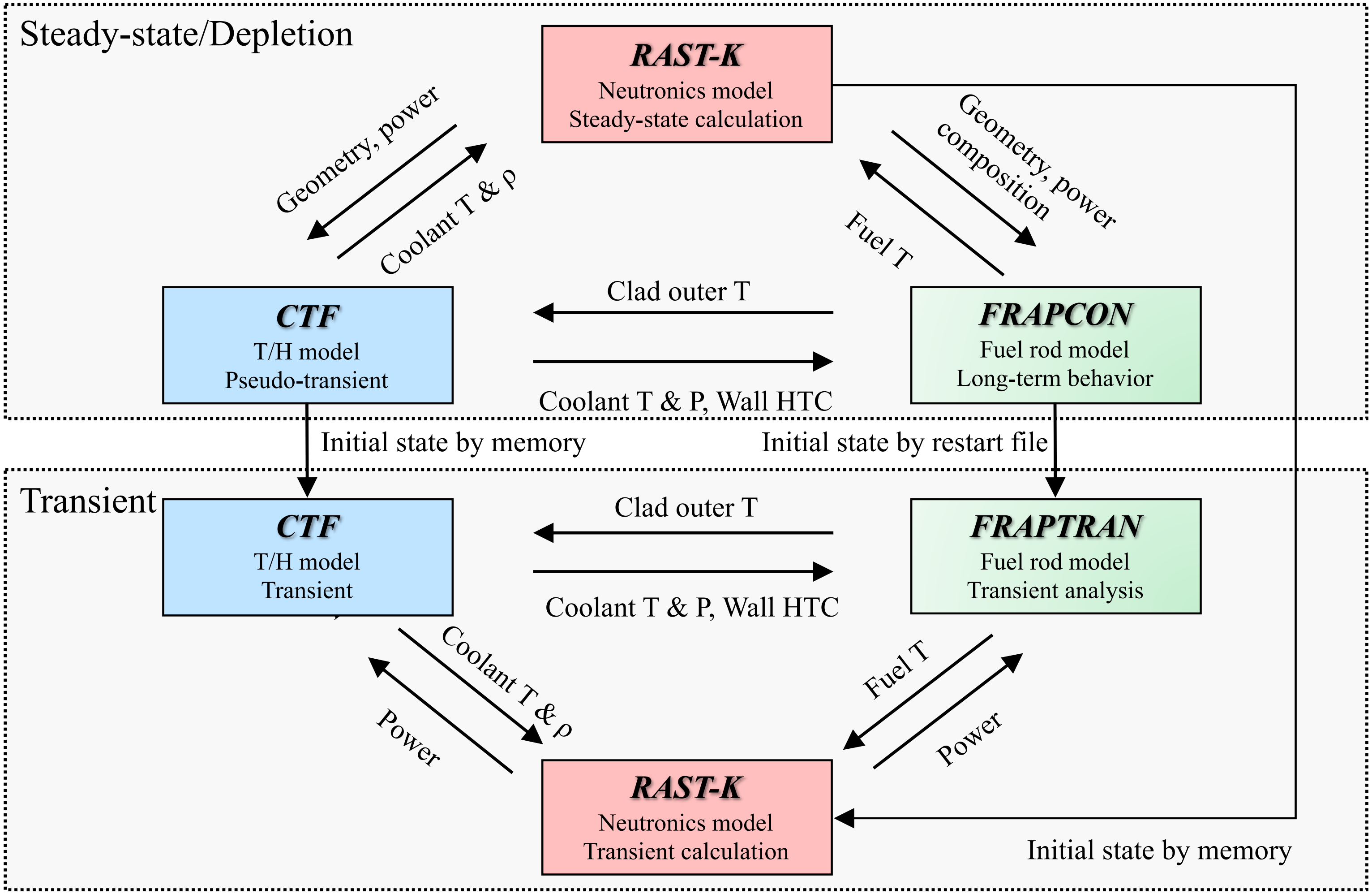
- **FRAPI**
  - **Initialization**
  - **Time-step advancing**
  - **Data exchange**
  - **Data saving and loading on memory or file**
  - **Writing restart file**
  - **Multi-rod simulation**



Coupling Parameters

- **Data exchange between coupled code**
  - **Power ⇔ Coolant ⇔ Fuel**





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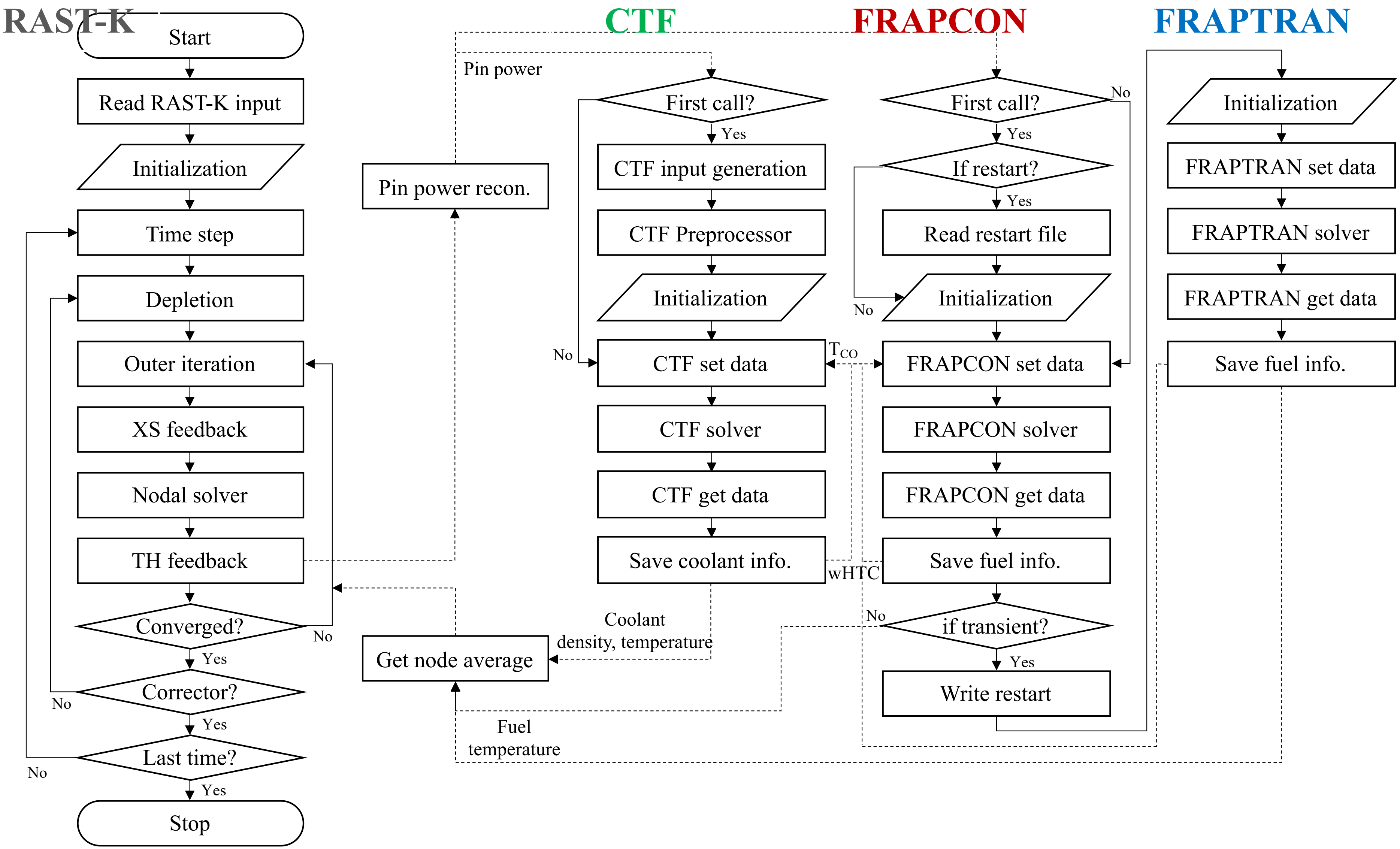
Coupling Algorithm

- **Flowchart of coupled code**



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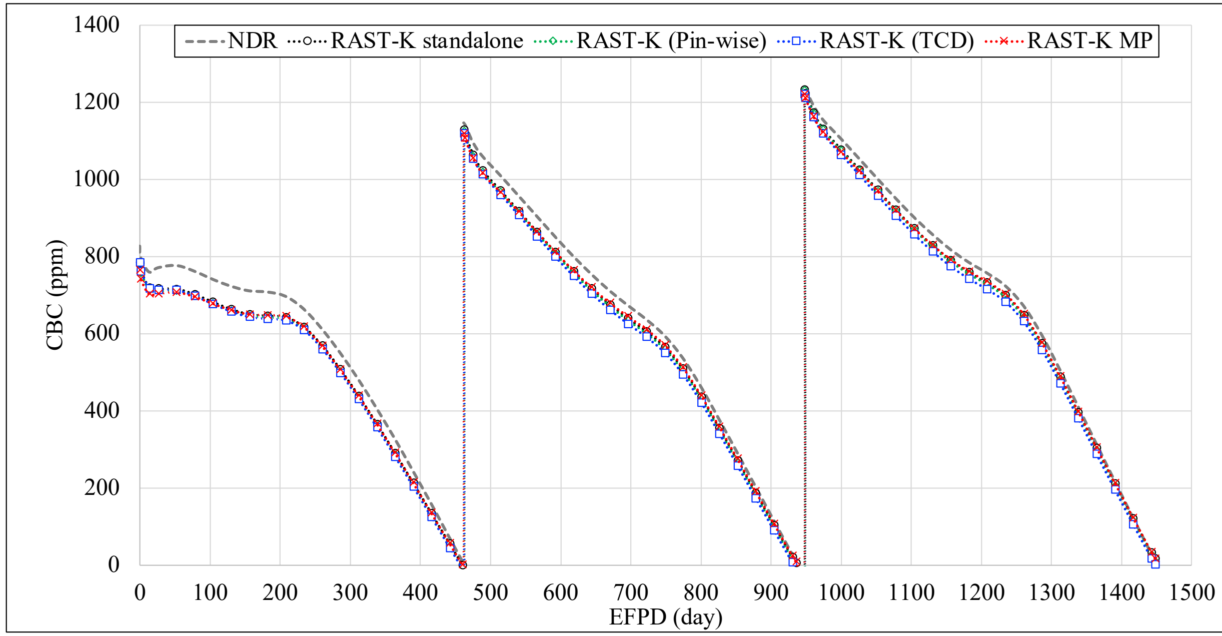
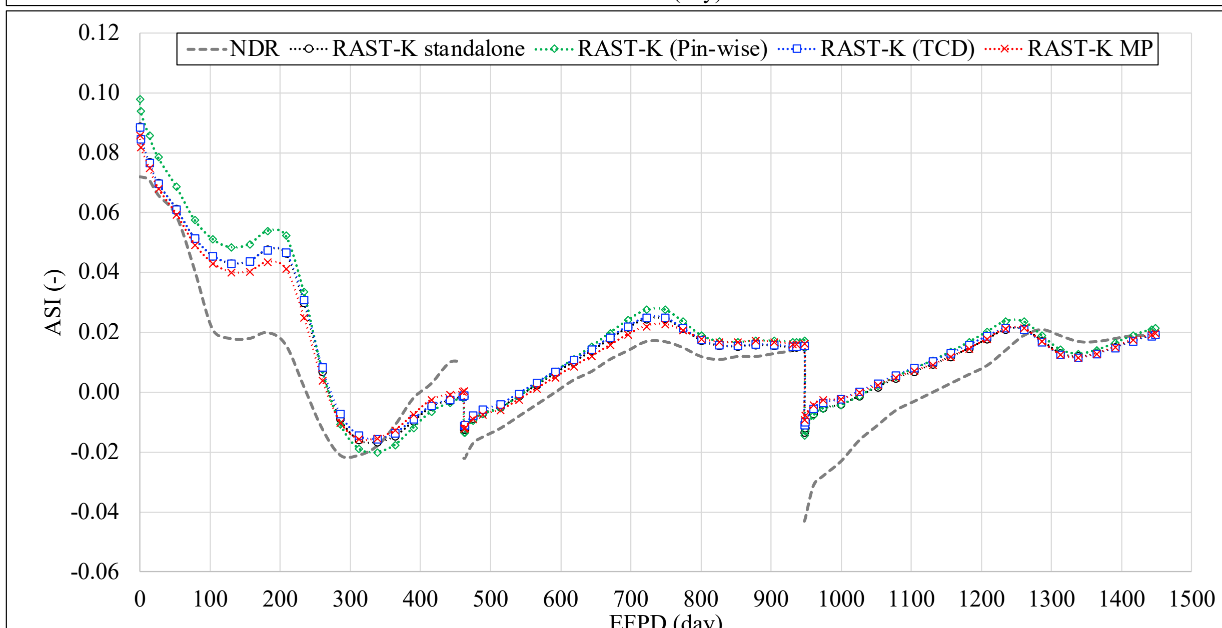
Depletion Calculation using RAST-K MP

- **APR1400**
  - **Cycle 1 to 3**
  - **241 FA**
  - **56,876 pins**
  - **3983MWth**

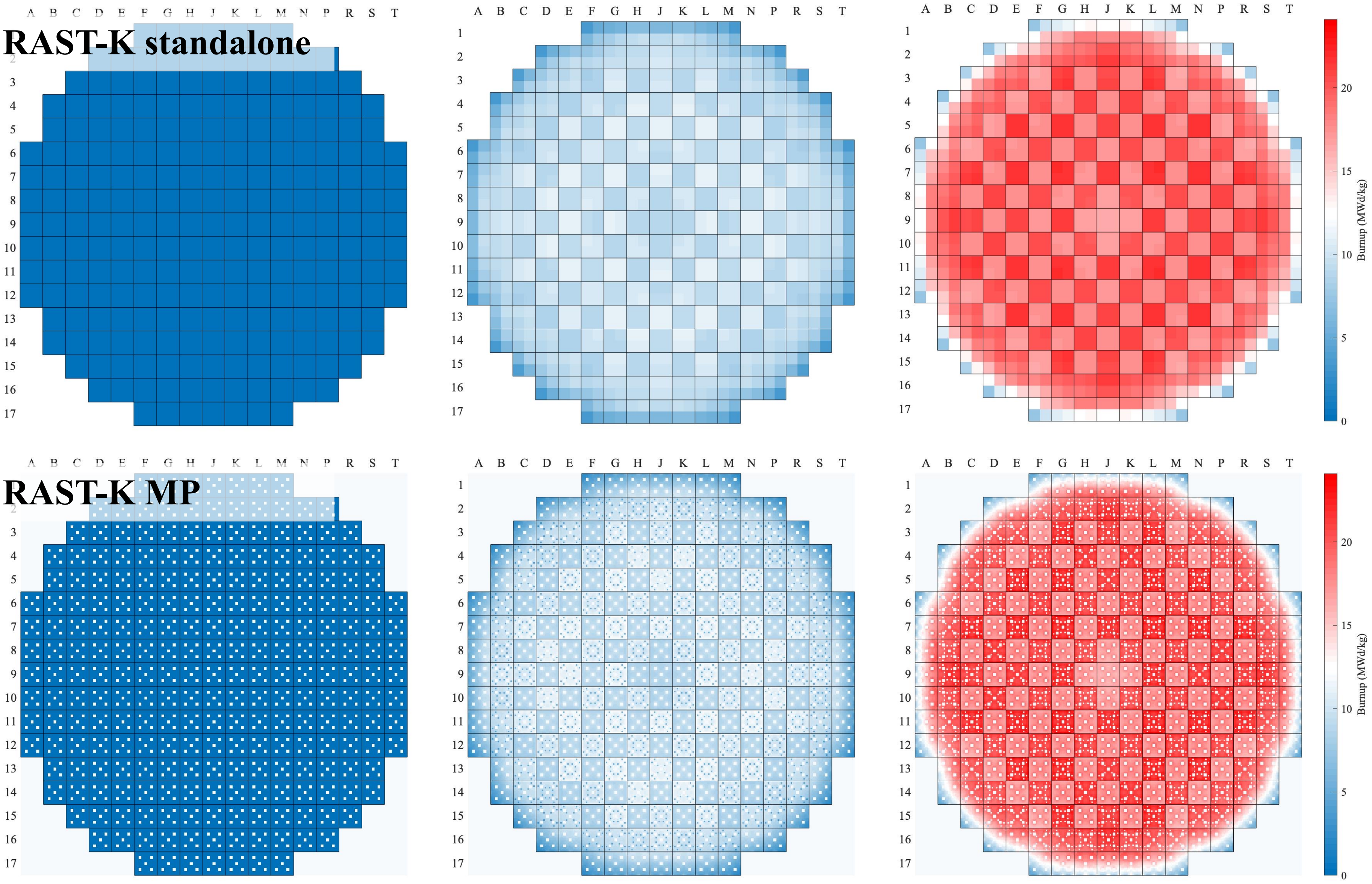
	J	K	L	M	N	P	R	S	L
9	O	O	T	O	F	O	F	T	F
10	O	F	O	F	O	F	O	F	T
11	T	O	T	O	T	O	T	F	F
12	O	F	O	F	O	F	O	F	T
13	F	O	T	O	T	O	F	T	
14	O	F	O	F	O	F	T	T	
15	F	O	T	O	F	T	T		
16	T	F	F	F	T	T			
17	F	T	F	T					





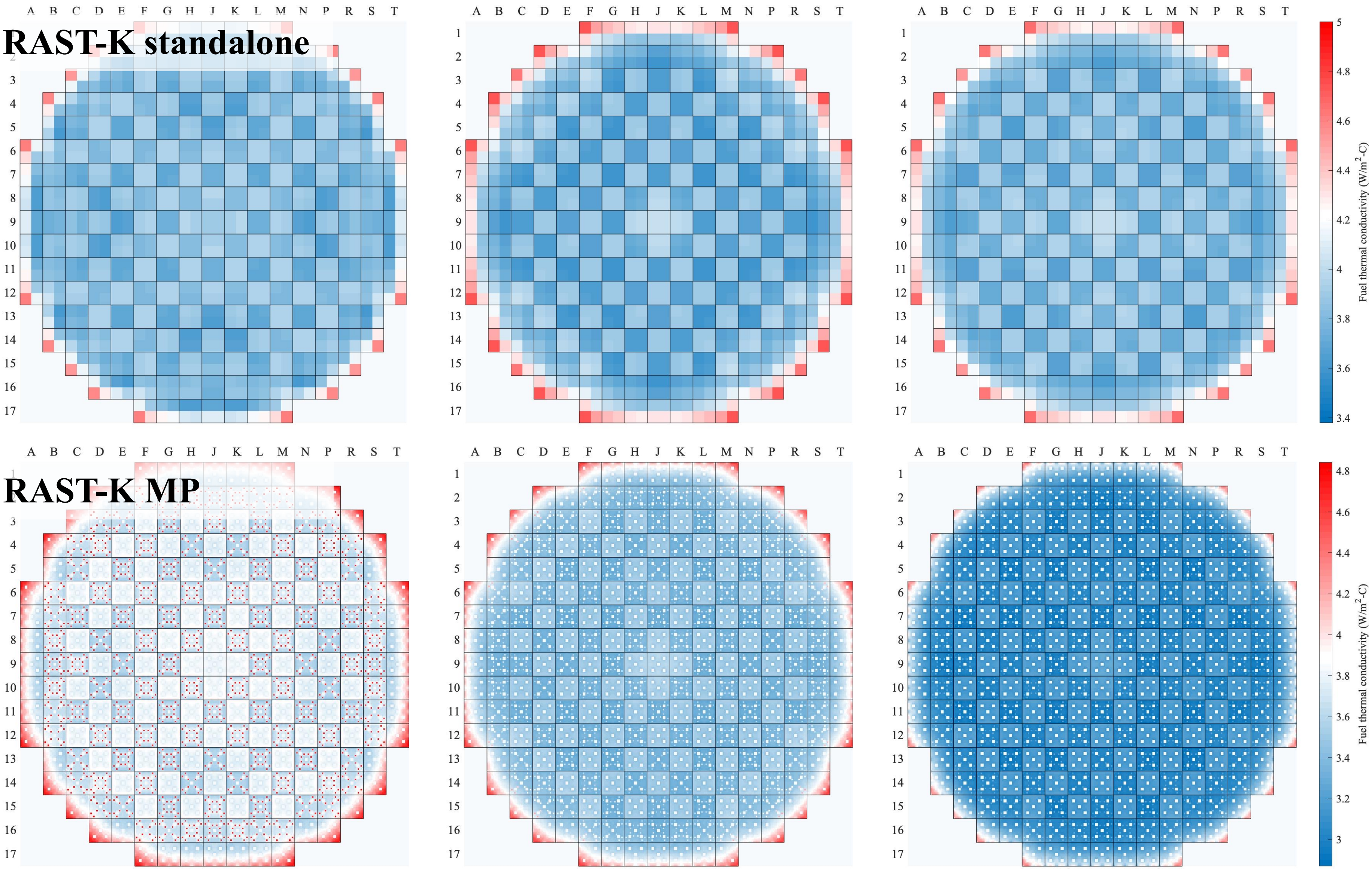
Depletion Calculation Result

- **Burnup at Cycle 1 (BOC/MOC/EOC)**



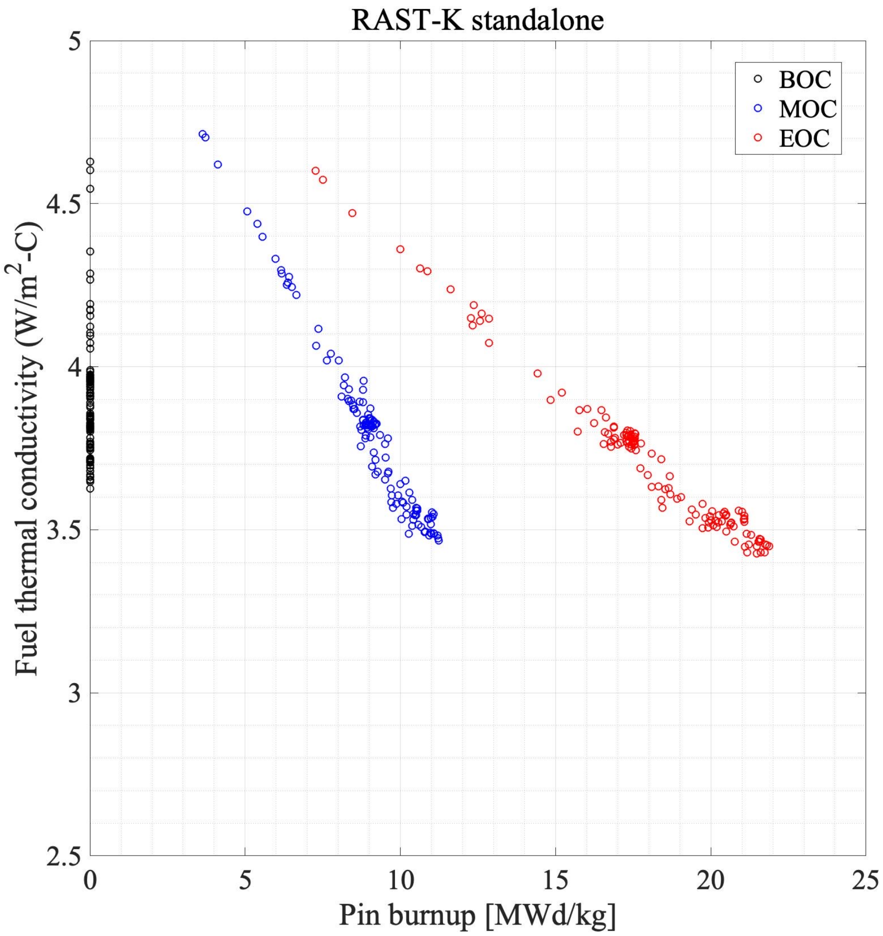
Depletion Calculation Result

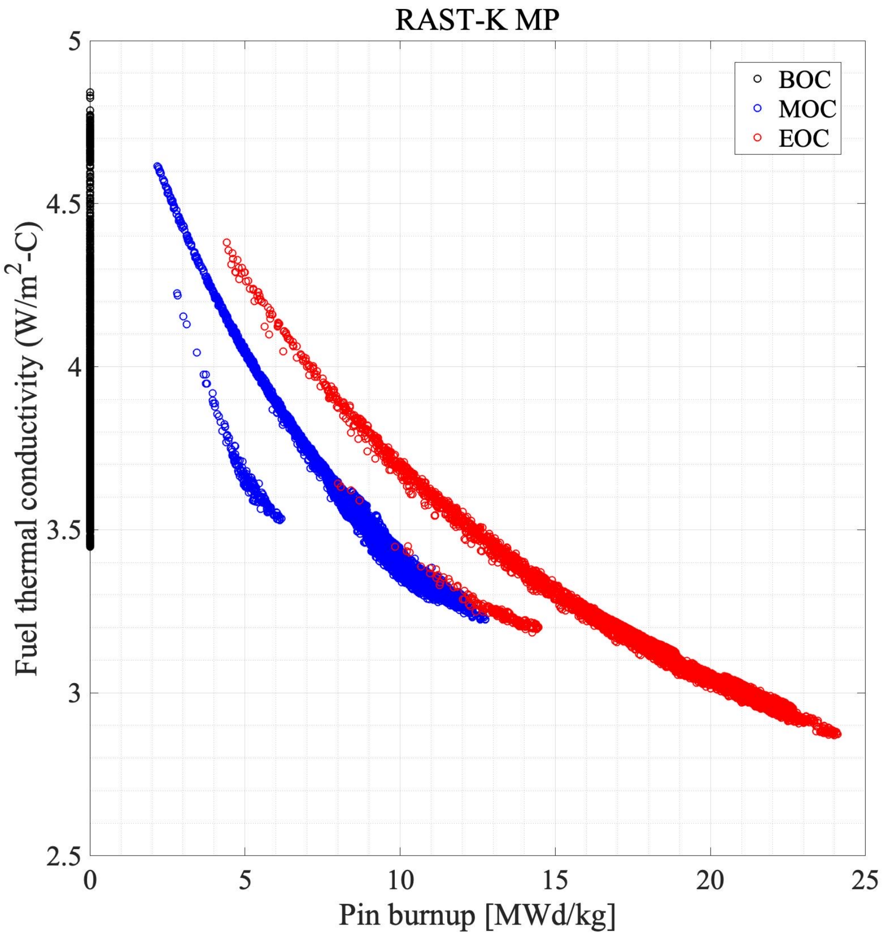
- **Fuel Thermal Conductivity at Cycle 1 (BOC/MOC/EOC)**



Depletion Calculation Result

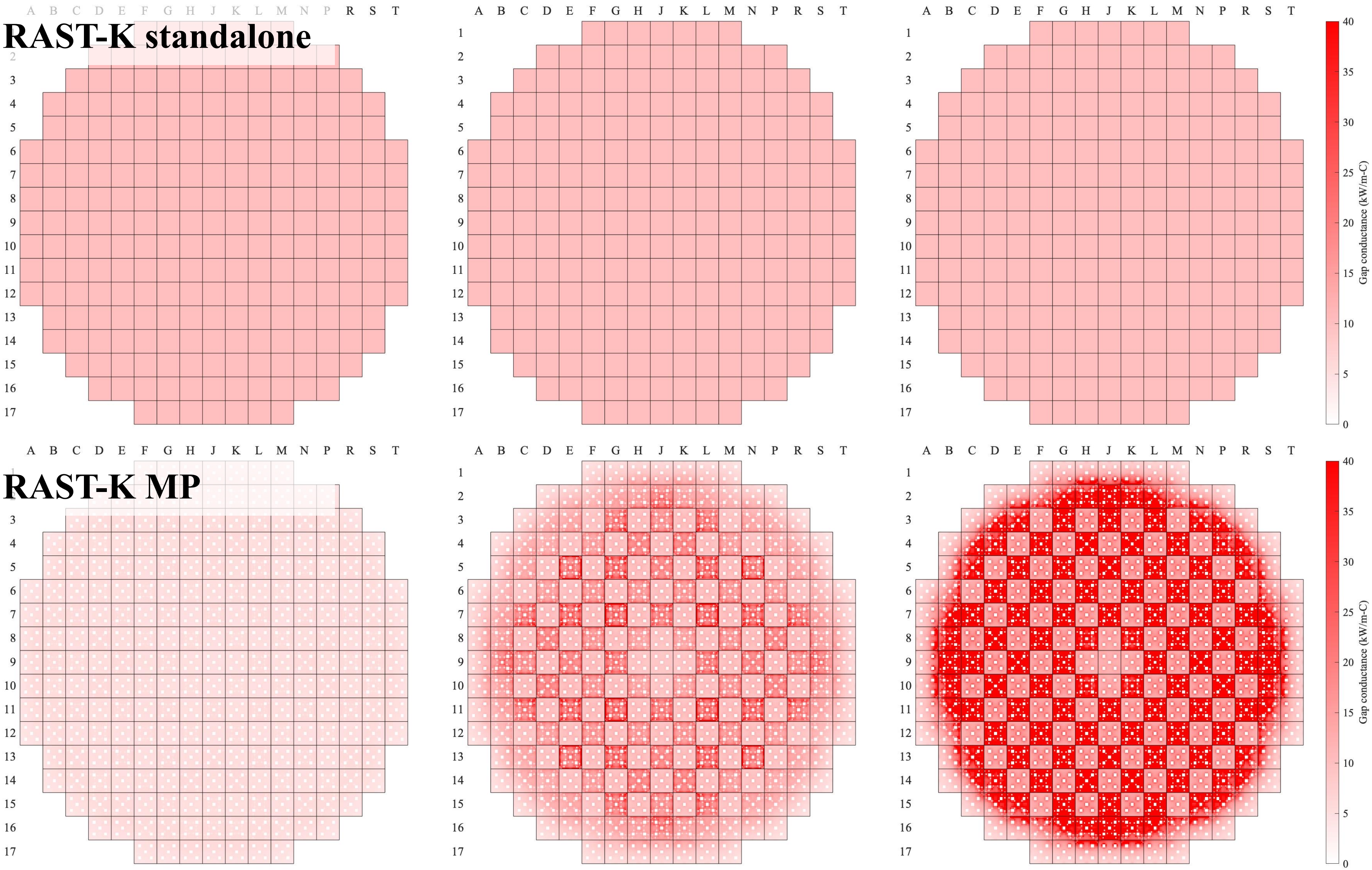
- **Fuel Thermal Conductivity vs. Burnup**





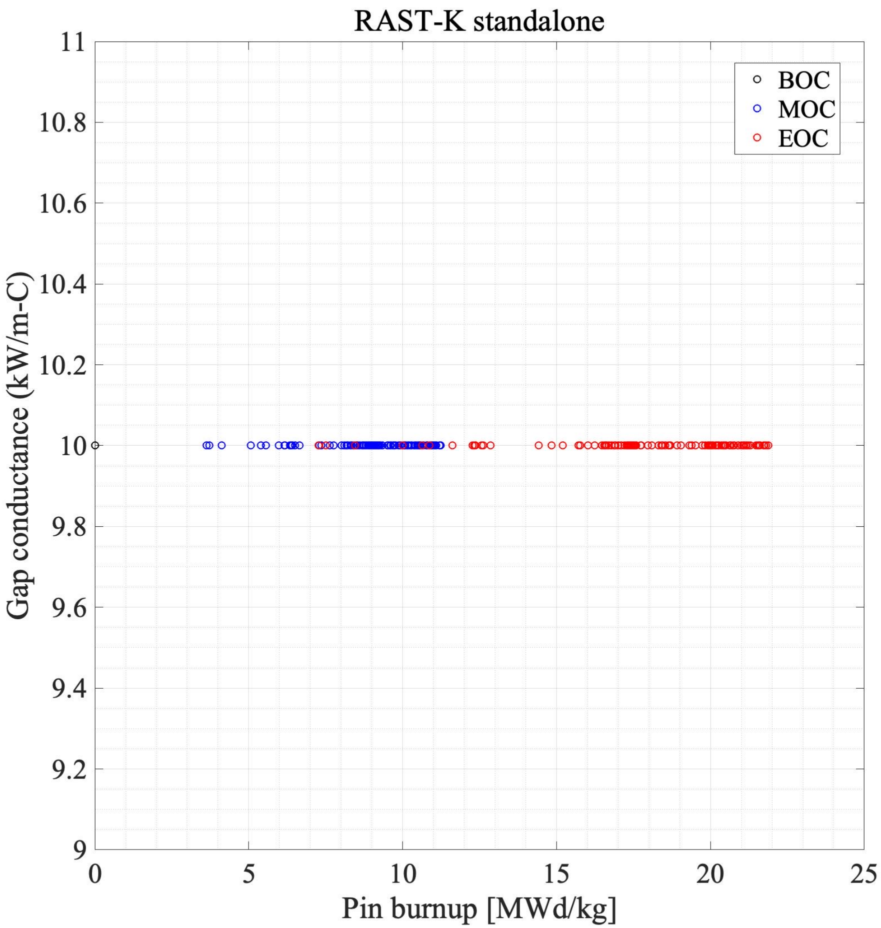
Depletion Calculation Result

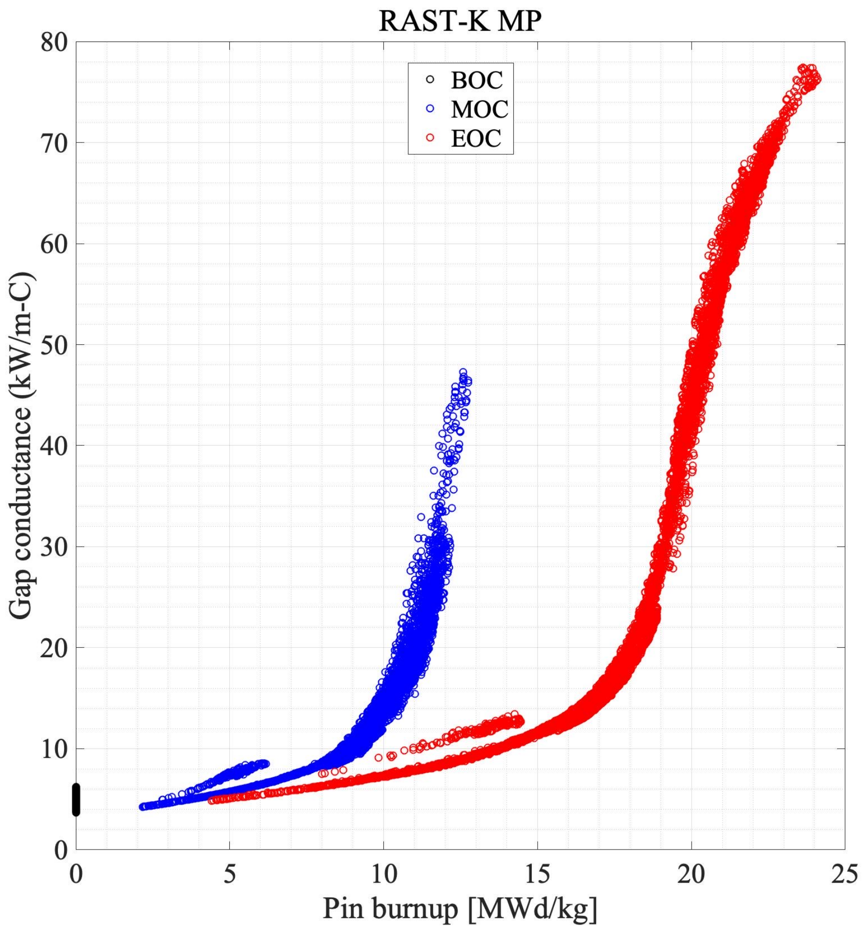
- **Gap Conductance at Cycle 1 (BOC/MOC/EOC)**



Depletion Calculation Result

- **Gap Conductance vs. Burnup**





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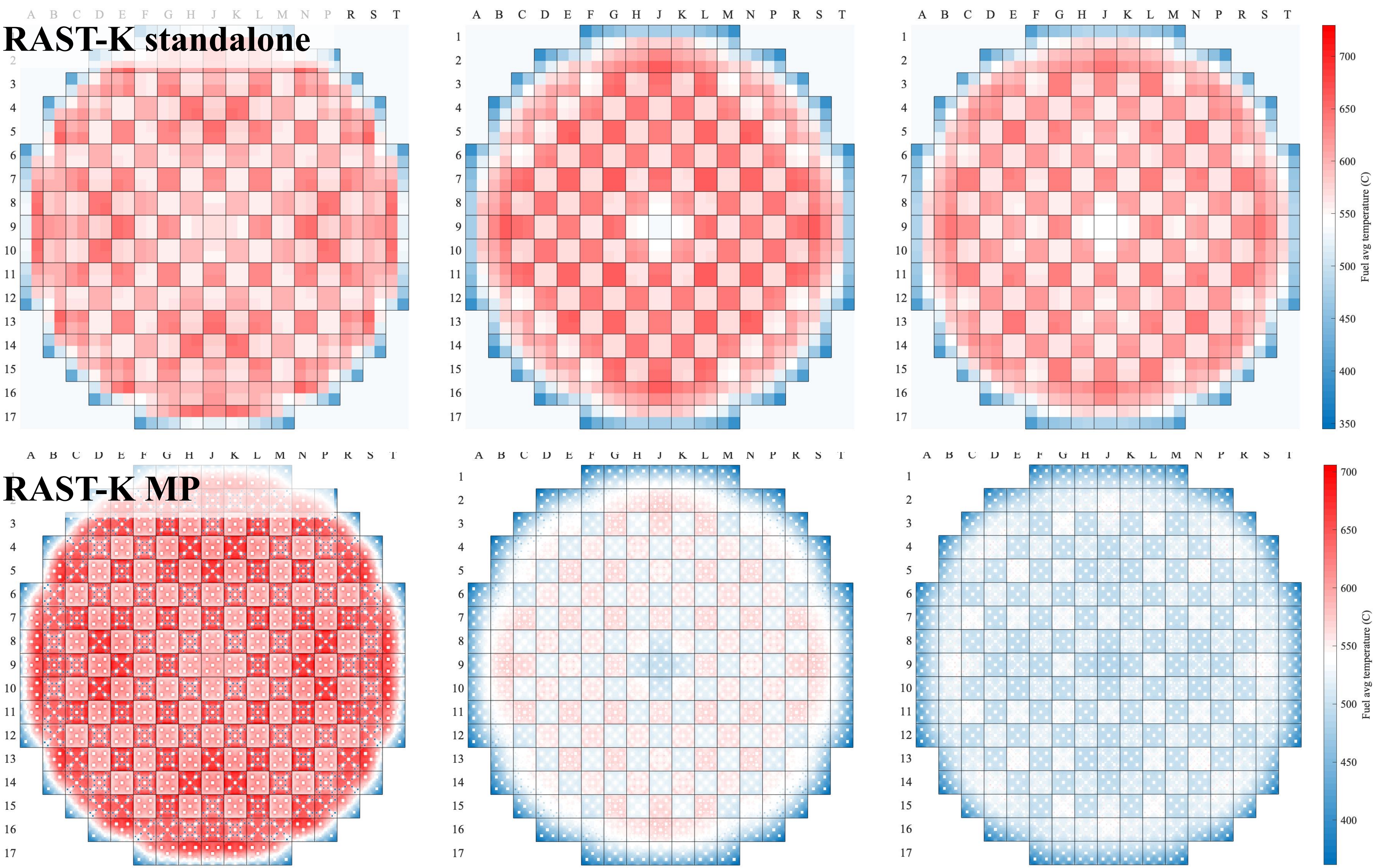
Depletion Calculation Result

- **Fuel Average Temperature at Cycle 1 (BOC/MOC/EOC)**



Depletion Calculation Result

▪ Summary

Compared to Measured		NDR	RAST-K standalone	RAST-K MP
CBC	Mean	-2.85	1.26	1.18
	Abs. STD	27.10	32.89	33.45
ASI	Mean	0.0004	0.0013	0.0009
	Abs. STD	0.0144	0.0131	0.0126
FA Power	Mean	0.002	0.003	0.003
	Abs. STD	0.019	0.018	0.018

▪ Performance

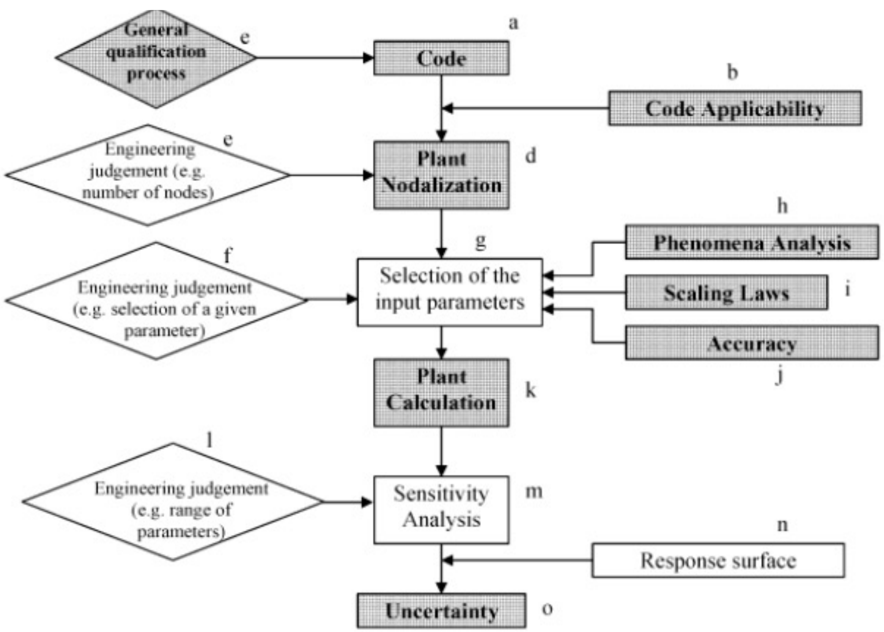
Components	RAST-K standalone	Ratio	RAST-K MP	Ratio
Total Simulation	**208.893**	-	**15477 (=4.3h)**	-
1. RAST-K	**206.724**	**98.96%**	**443.007**	**2.86%**
1.1 Initialize	24.040	11.51%	30.278	0.20%
1.2 Neutronics	18.243	8.73%	48.903	0.32%
1.3 TH feedback	19.449	9.31%	15.551	0.10%
1.4 XS feedback	48.401	23.17%	114.528	0.74%
1.5 Depletion	81.538	39.03%	103.927	0.67%
1.6 Pin power recon.	1.721	0.82%	65.513	0.42%
1.7 Write	13.332	6.38%	64.307	0.42%
2. CTF	-	-	**8637 (=2.4h)**	**55.80%**
3. FRAPCON	-	-	**6395.342 (=1.8h)**	**41.32%**

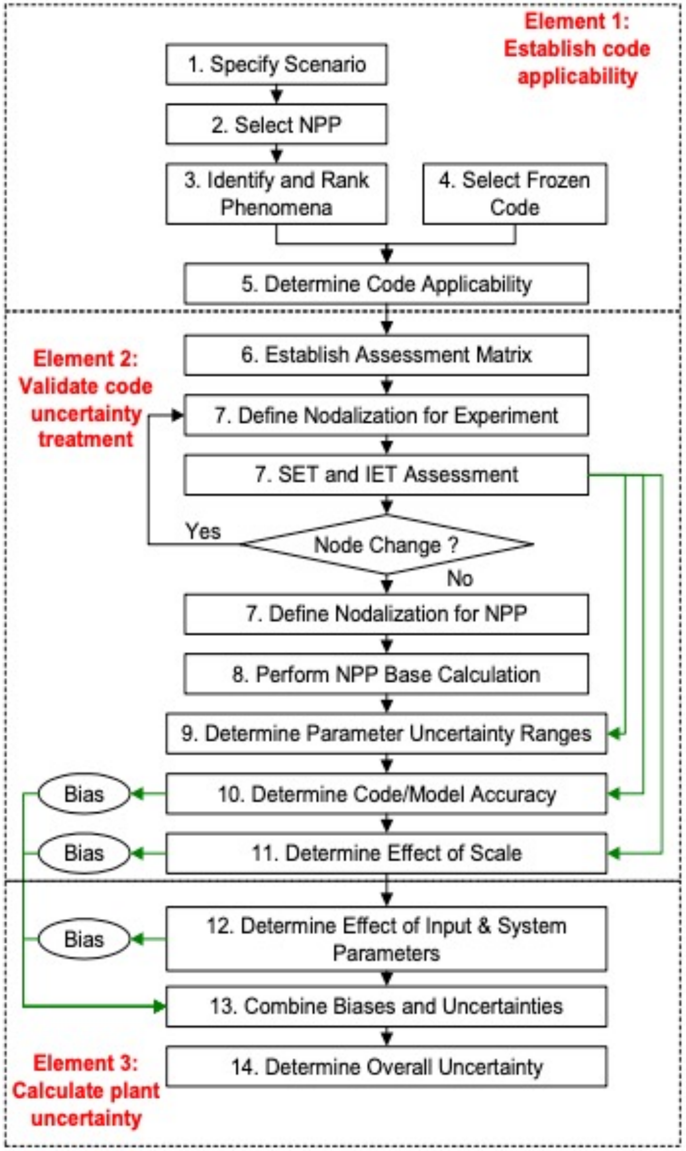
3. BEPU Methodology

Development of BEPU Methodology using Multi Physics coupling code based on RAST-K

Review of BEPU Methodology

- **CSAU**
  - **Code Scaling, Applicability and Uncertainty**
    - published in 1990 by the U.S.NRC
    - RELAP5/MOD3.1 for PCT during LBLOCA
- **K-REM**
  - **KINS-Realistic Evaluation Methodology**
    - originally developed based on CSAU in 1991
    - RELAP5/MOD3.1K for PCT during LBLOCA





Review of BEPU Methodology

- $PCT_{FINAL} = PCT_{95/95} + B_{SCALE} + B_{SET} + B_{IET} + B_{PLANT}$
  - B_{SET}, B_{IET}
    - Bias from the discrepancy between calculation result and experiment result from SET/IET
  - B_{SCALE}
    - Bias from the scaling distortion of phenomena or model of code
  - B_{PLANT}
    - Bias from the uncertainty of operating parameter of plant, which is excluded in step 3
  - $PCT_{95/95}$
    - Combination of PCT and statistical uncertainty from individual models and variables with 95% probability level and 95% confidence level
    - $PCT_{95/95}$ was determined through a large number of MC simulation for the response surface methodology produced from the sampled code calculation results, which was similar to the CSAU method
    - The 95/95 tolerance limit of PCT can be directly calculated without response surface methodology in non-parametric statistics based on minimum number of simulation from Wilks's formula

UQ Methodology

▪ Stochastic sampling method

- **Latin Hypercube Sampling**
  - Partitioning the CDF into even region, randomly pickup in each region
  - Available to sample Uniform/Normal distribution

▪ Proper number of samples?

- **Wilks' non-parametric formula:** $\sum_{j=0}^{N-p} \frac{N!}{(N-j)!j!} \alpha^j (1-\alpha)^{N-j} \geq \beta$
- **Ex. Wilks' theorem for a one-sided 3rd-order statistics tolerance limit**

$$1 - \alpha^N - N(1-\alpha)\alpha^{N-1} - \frac{N*(N-1)}{2}(1-\alpha)^2\alpha^{N-2} \geq \beta$$

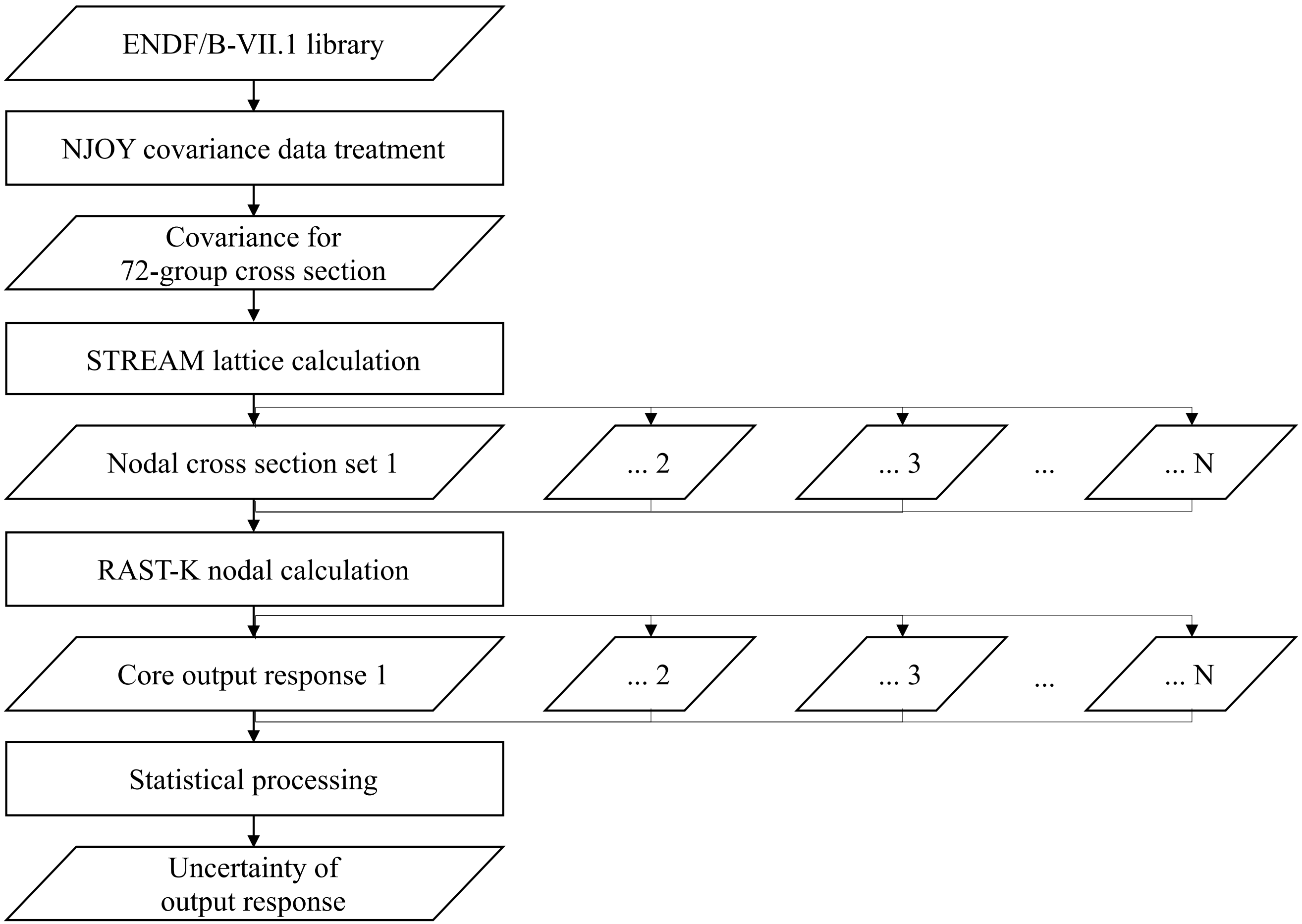
Various Tables for statistically meaningful number of simulations are derived from the above Equation (2) for different orders' one-sided approach, Equation (4) for the 1st order two-sided approach and Equation (5) for the 2nd order two-sided approach. Table 1 to Table 3 summarize the minimum numbers of code runs necessary for the 1st, 2nd and 3rd order statistics, respectively, when users require to perform the simulations for the one-sided approach. Table 4 and Table 5 summarize the numbers for the 1st and 2nd order statistics each for the two-sided approach. For example, the minimum number of required code runs for the condition of 95th percentile / 95 % confidence level are:

- 59 for 1st order one-sided,
- 93 for 2nd order one-sided,
- 124 for 3rd order one-sided,
- 146 for 1st order two-sided (against the present 93) and
- 221 for 2nd order two-sided.

Stochastic Sampling Method

▪ Nuclear Data Perturbation

- 72g covariance matrix for 144 nuclides
- ENDF/B-VII.1 library



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Stochastic Sampling Method

▪ Input Parameter Perturbation

- **TH simulation**
  - Core power, Coolant flow rate, System pressure, Inlet temperature
  - Turbulent-mixing coefficient, Weight of void drift model
  - Spacer grid width, Spacer grid loss coefficient, Guide tube diameter
  - DMHR
- **FP simulation**
  - Pellet density, Pellet outer diameter, Initial gap thickness, Cladding thickness, Rod fill gas pressure, Plenum length, U-235 concentration, Gadolinia enrich, Pellet roughness, Cladding roughness
  - Dish shoulder width, Dish height
- **Reference**
  - UAM Benchmark Phase I & II
  - Paper (Experimental Database of Two-Phase Natural Circulation with Local Measurements, PNE, 116:124, 2019)
  - NUREG/CR-7001, 7022, 7024
  - Assumption

UQ for Depletion Calculation

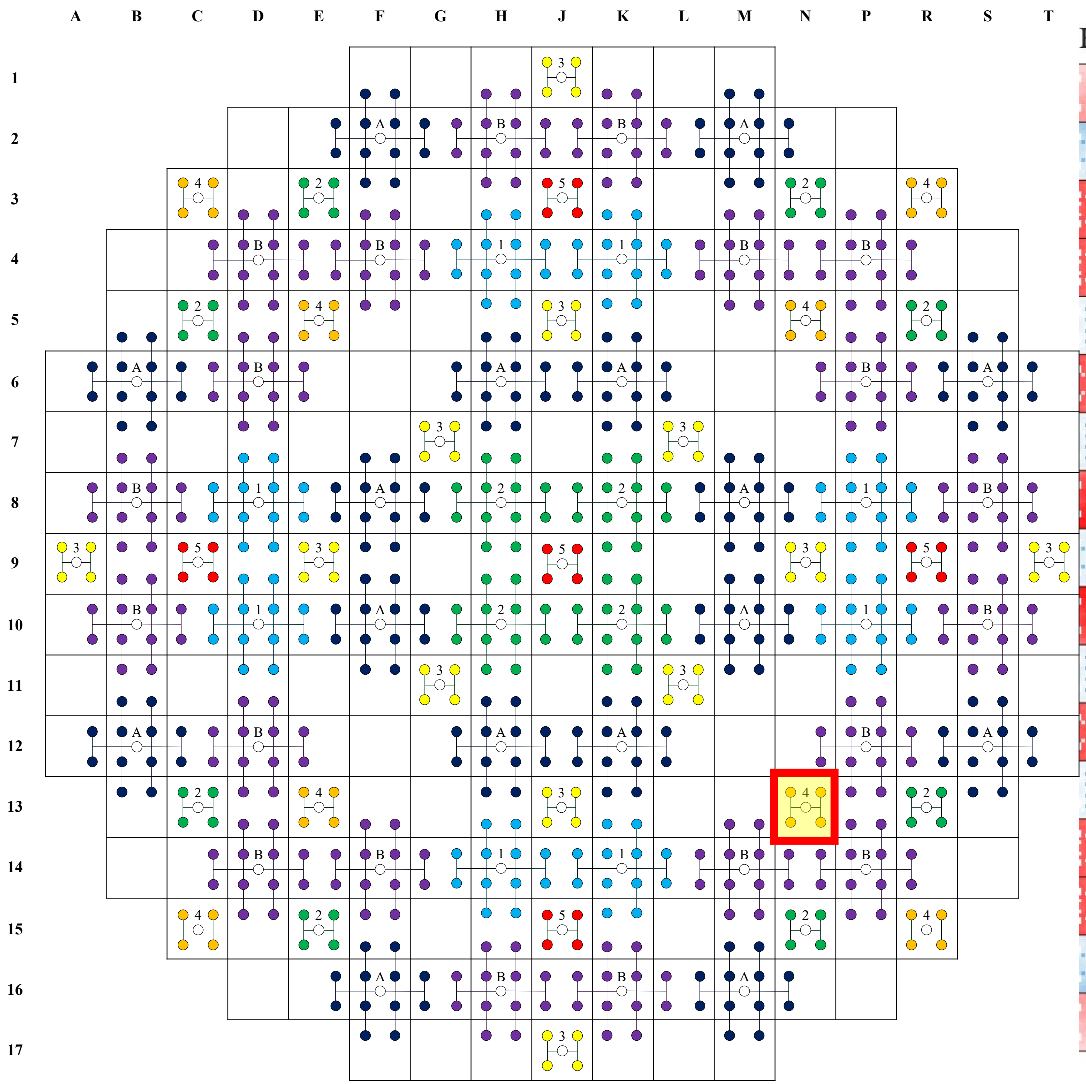
▪ Summary of UQ for depletion calculation

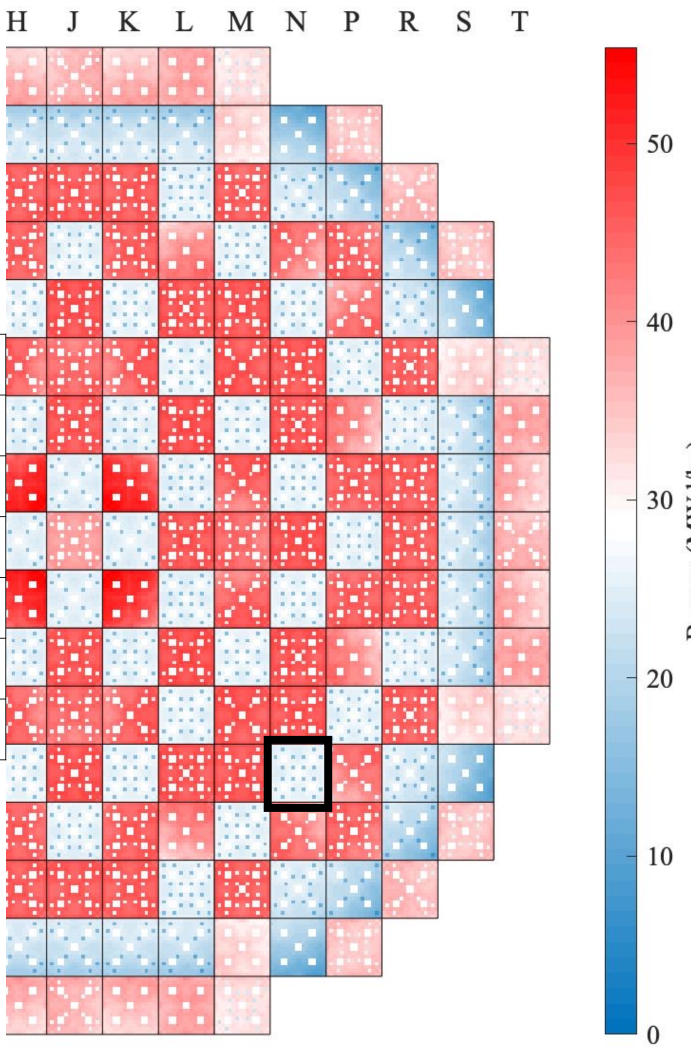
- **Uncertainty of design parameter mainly come from nuclear data**
- **However, uncertainty of PFT come from ?**

Parameter	State	All	Input parameter	Nuclear data
CBC	BOC	1231.91 ± 79.77	1232.72 ± 2.47	1232.07 ±80.00
	MOC	743.58 ± 69.46	741.86 ± 4.08	743.64 ± 69.63
	EOC	-10.97 ± 54.39	-6.06 ± 7.79	-10.60 ± 53.76
ASI	BOC	-0.0071 ± 0.0076	-0.0083 ± 0.0004	-0.0073 ± 0.0066
	MOC	0.0181 ± 0.0067	0.0181 ± 0.0022	0.0179 ± 0.0046
	EOC	0.0166 ± 0.0127	0.0158 ± 0.0048	0.0167 ± 0.0118
Fq	BOC	1.6134 ± 0.0201	1.6011 ± 0.0027	1.6124 ± 0.0212
	MOC	1.6756 ± 0.0173	1.6629 ± 0.0055	1.6748 ± 0.0171
	EOC	1.6041 ± 0.0383	1.5938 ± 0.0148	1.6021 ± 0.0343
Max. PFT	BOC	1262.01 ± 21.94	1256.64 ± 14.66	1261.97 ± 14.43
	MOC	1349.24 ± 23.31	1337.54 ± 16.69	1348.76 ± 16.54
	EOC	1399.38 ± 29.25	1388.52 ± 19.94	1395.24 ± 24.28

REA Calculation: EOC HZP

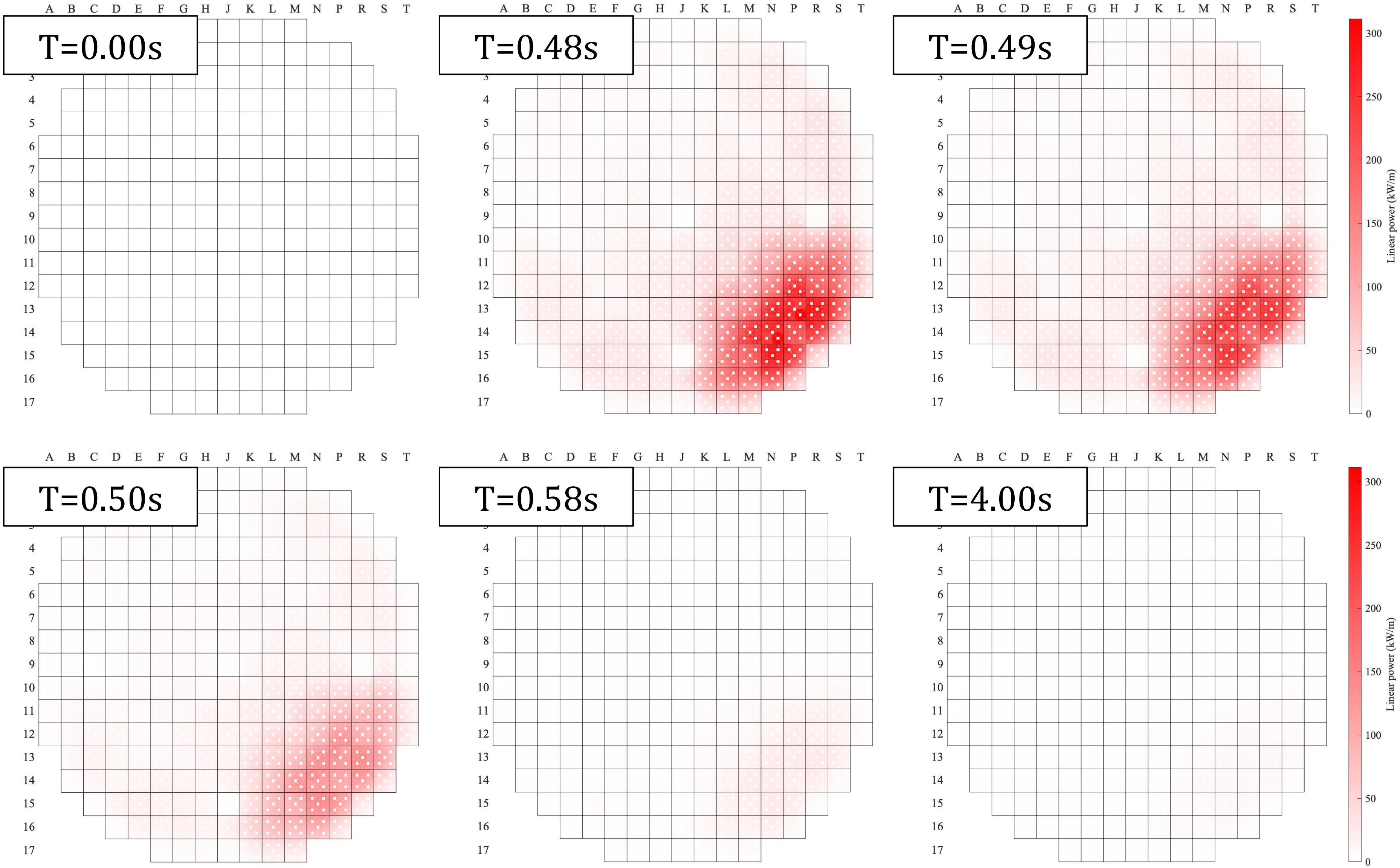
- **Scenario**
  - **Initially R5, R4 Bank fully insertion, R3 40% insertion**





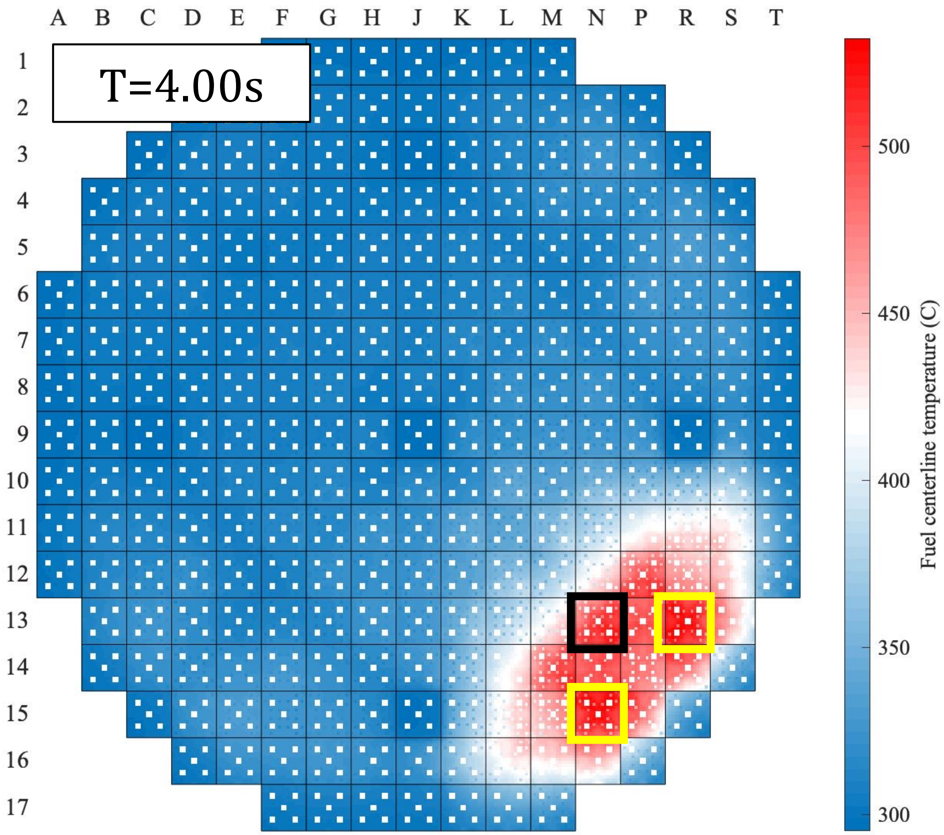
REA Calculation: EOC HZP

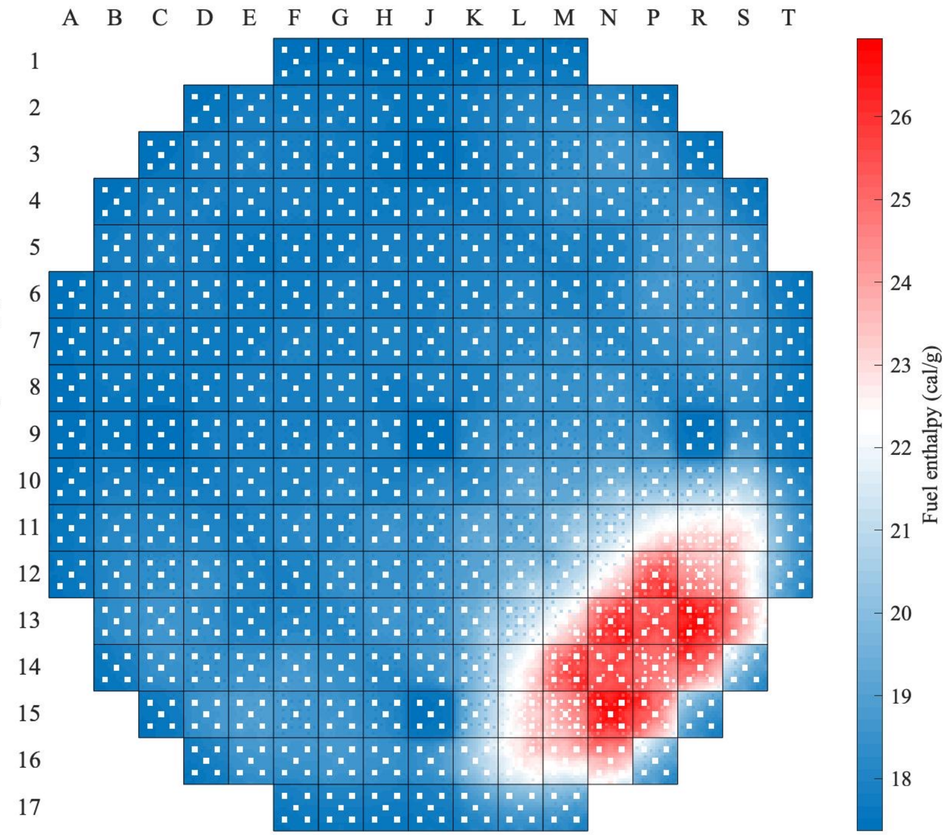
- **Transient Result (Linear pin power dist.)**



REA Calculation: EOC HZP

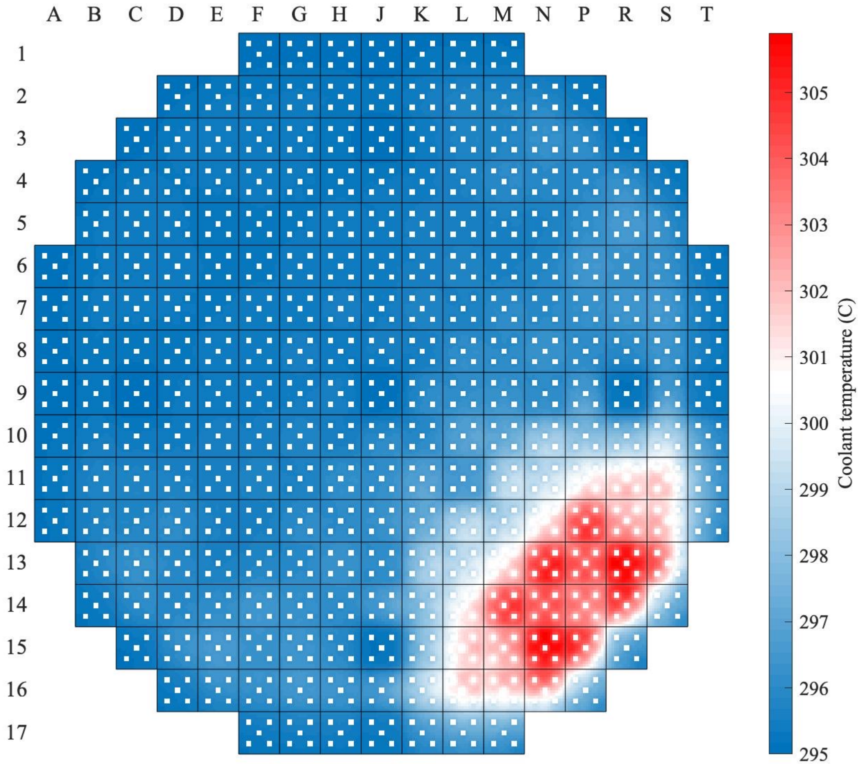
- **Transient Result**
  - **Maximum fuel centerline temperature**
  - **Maximum fuel enthalpy**
    - Peak at the end of transient

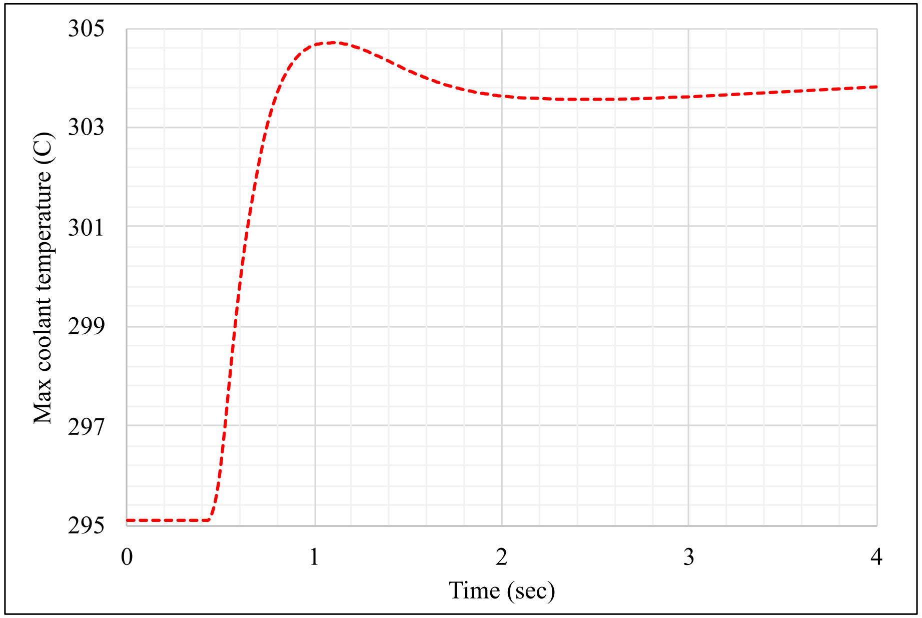


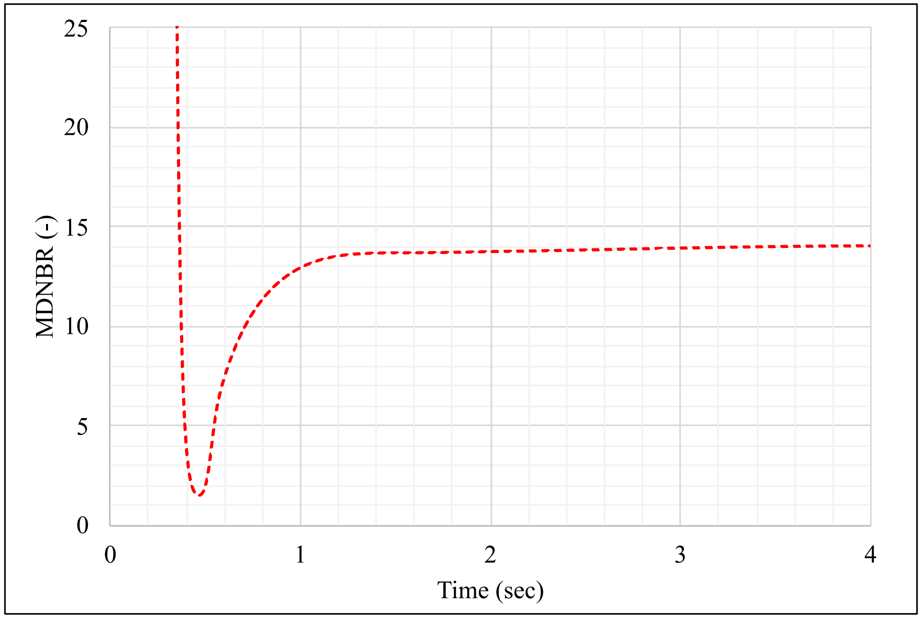


REA Calculation: EOC HZP

- **Transient Result**
  - **Max coolant temperature**
    - Rises more than 10 C from inlet
  - **MDNBR**
    - Heat capacity of fuel pellet







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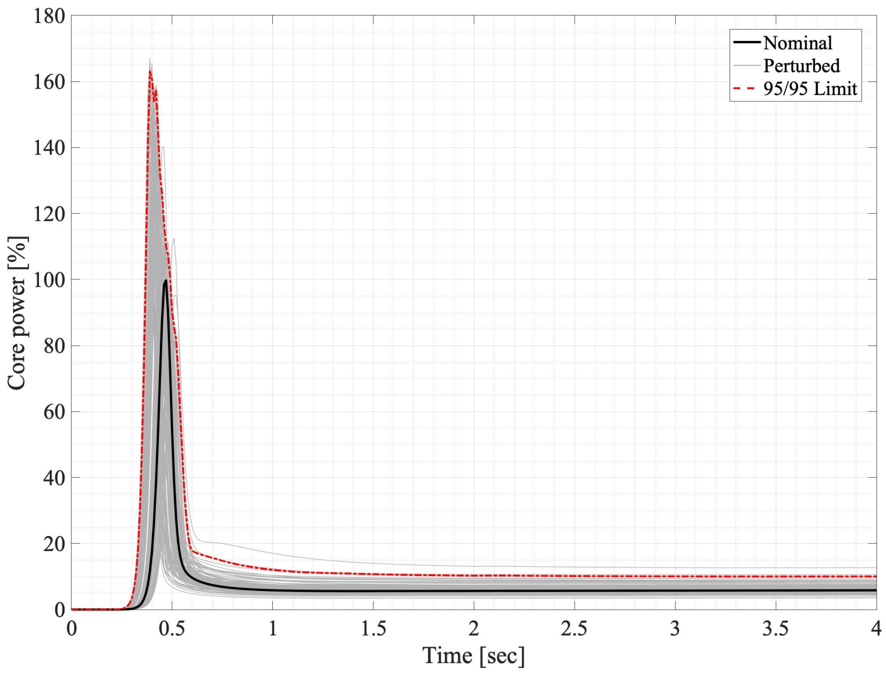
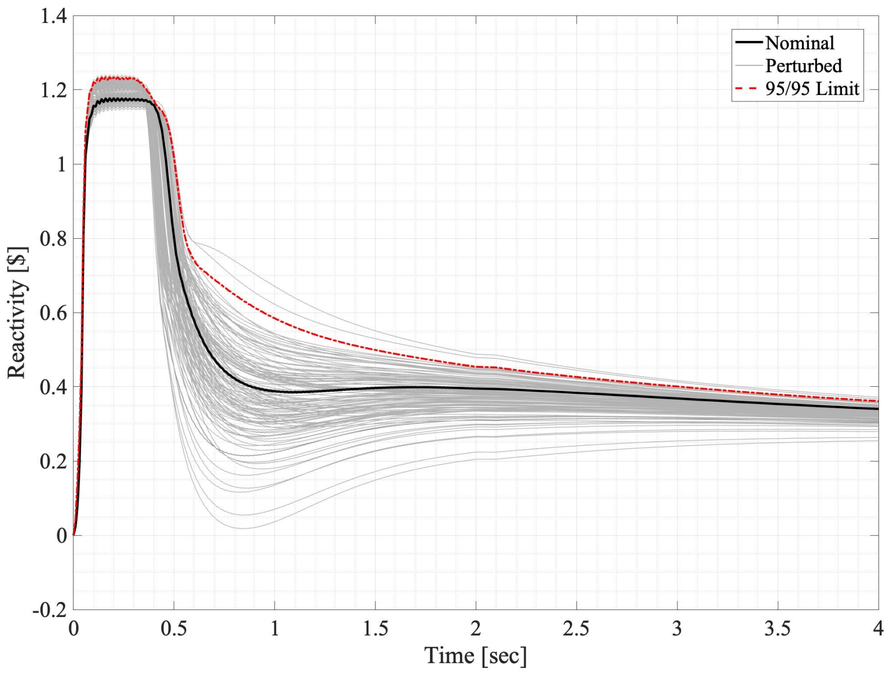
UQ for Transient Calculation: EOC HZP REA

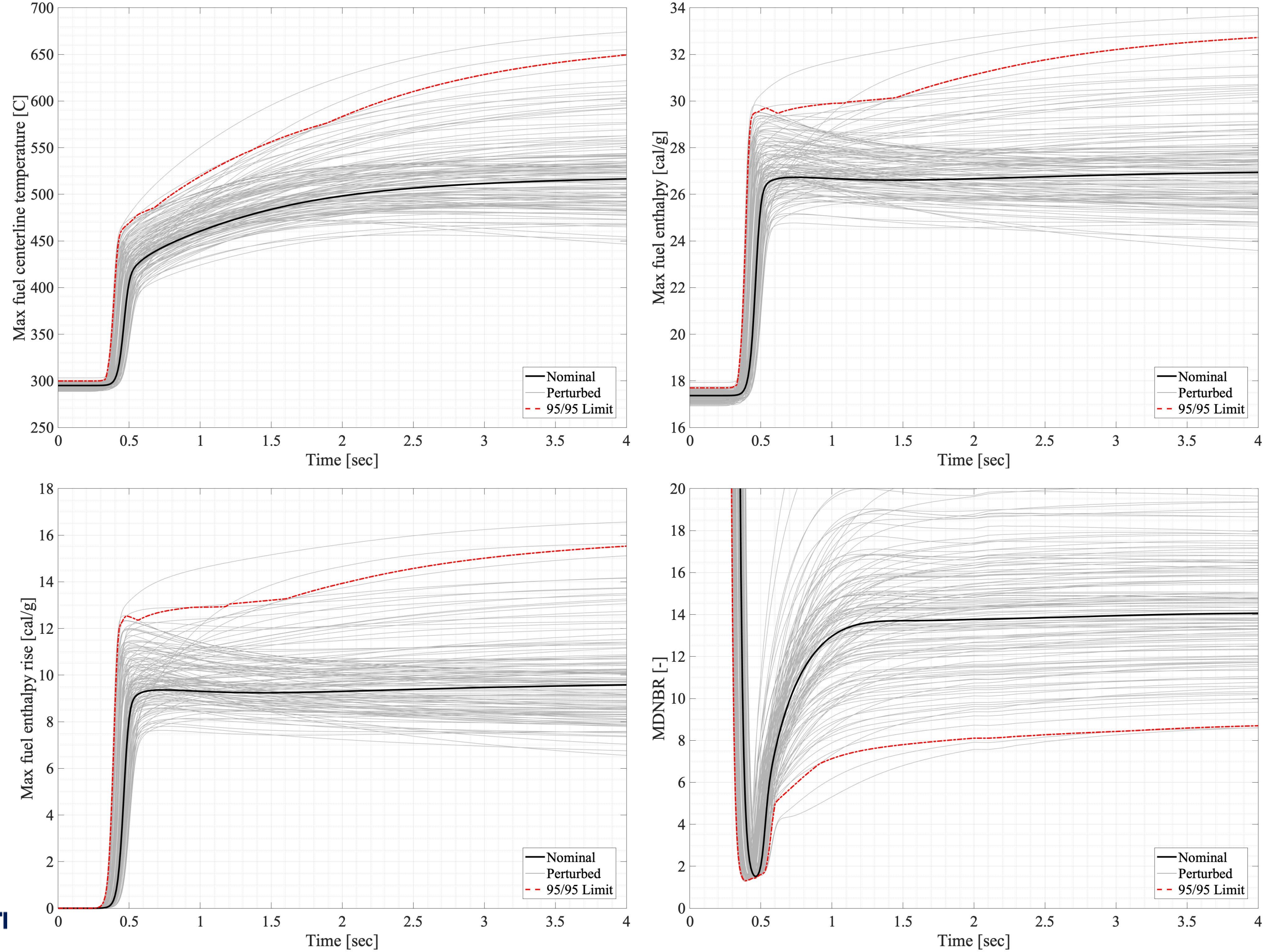
- **Transient Result**
  - **Black line = Nominal**
  - **Red line = 95th percentile among all perturbed sample**
    - 95% confidence that the true peak value is below the 95th tolerance limit





UQ for Transient Calculation: EOC HZP REA

- **Safety parameters**



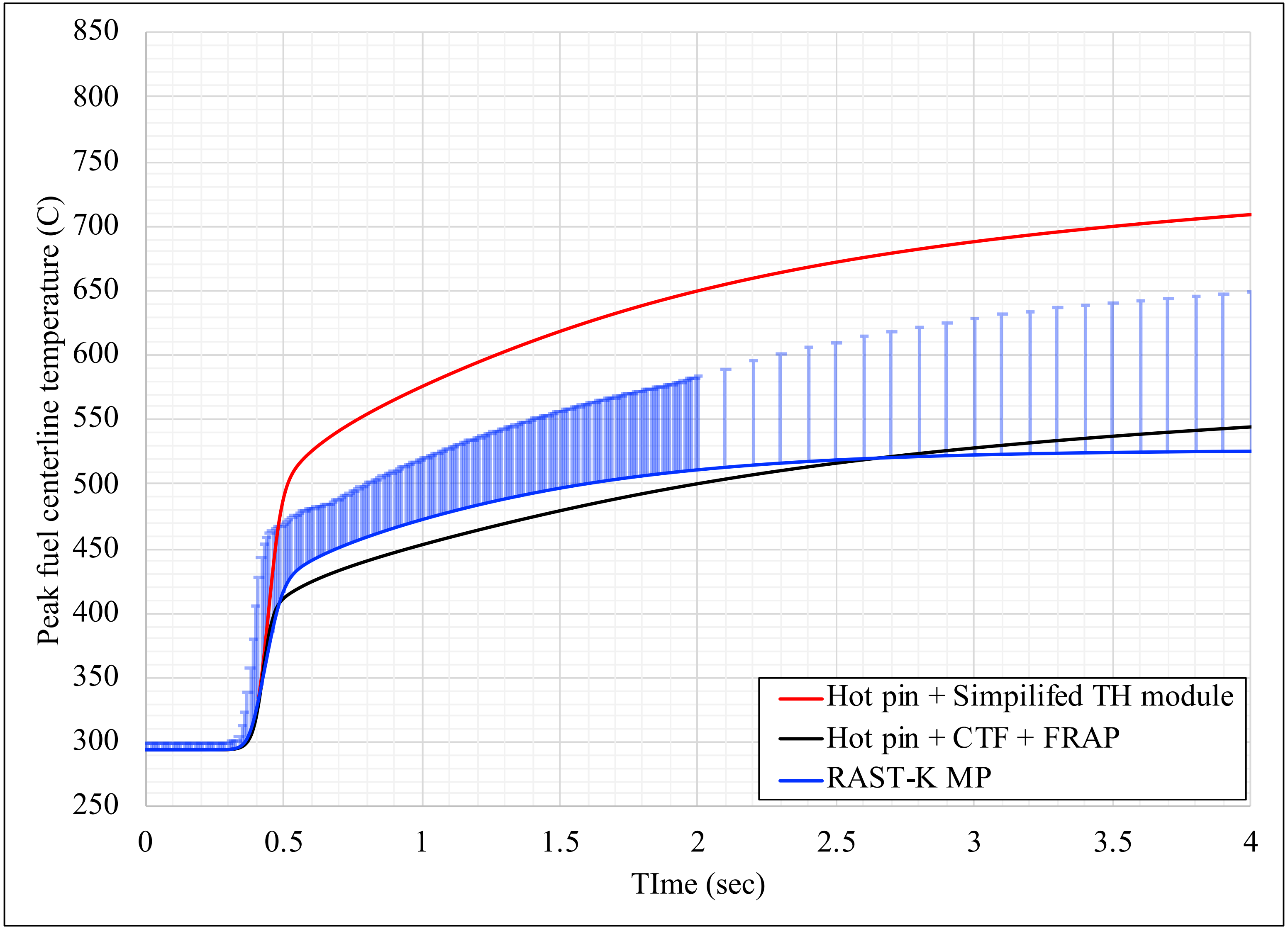
UQ for Transient Calculation: EOC HZP REA

- **Summary of UQ for EOC HZP REA**
  - **Current BEPU methodology reduce the safety margin?**

Parameter	Nominal	Mean ± Abs. STD	95/95 Tolerance Limit
Peak power (%)	99.73	117.86 ± 24.60	163.02
Peak reactivity ($)	1.177	1.194 ± 0.022	1.234
Peak fuel centerline temp. (C)	516.55	526.69 ± 42.62	649.43
Peak fuel enthalpy (cal/g)	26.95	27.96 ± 1.63	32.73
Peak fuel enthalpy-rise (cal/g)	9.58	10.61 ± 1.69	15.53
Peak outlet temperature (C)	296.61	296.5 ± 2.79	301.51
MDNBR (-)	1.517	1.476 ± 0.104	1.309

UQ for Transient Calculation: EOC HZP REA

- Hot pin + Simplified TH vs. Hot pin + CTF + FRAP vs. MP
  - Fuel centerline temperature



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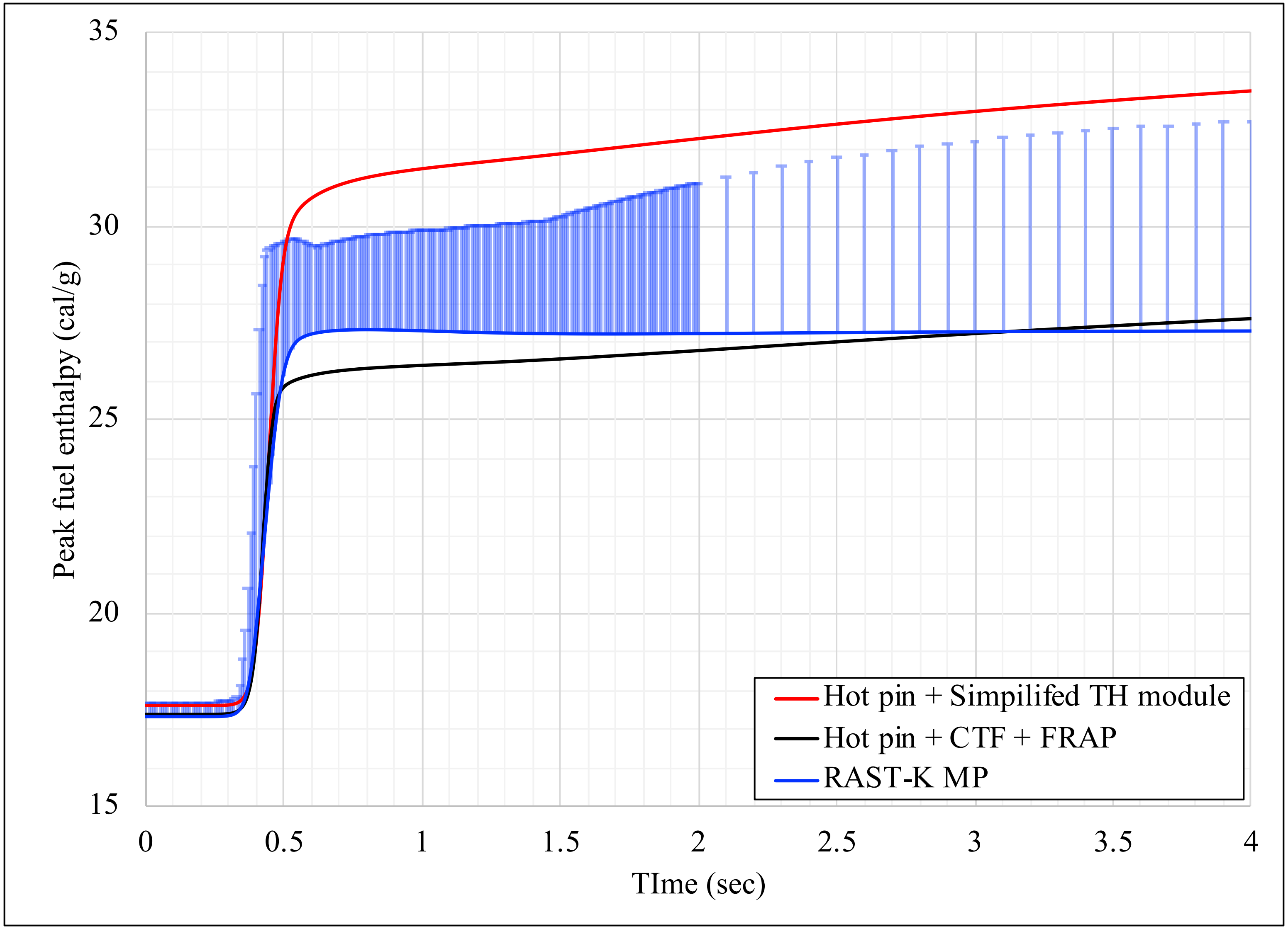
UQ for Transient Calculation: EOC HZP REA

- **Hot pin + Simplified TH vs. Hot pin + CTF + FRAP vs. MP**
  - **Fuel enthalpy**



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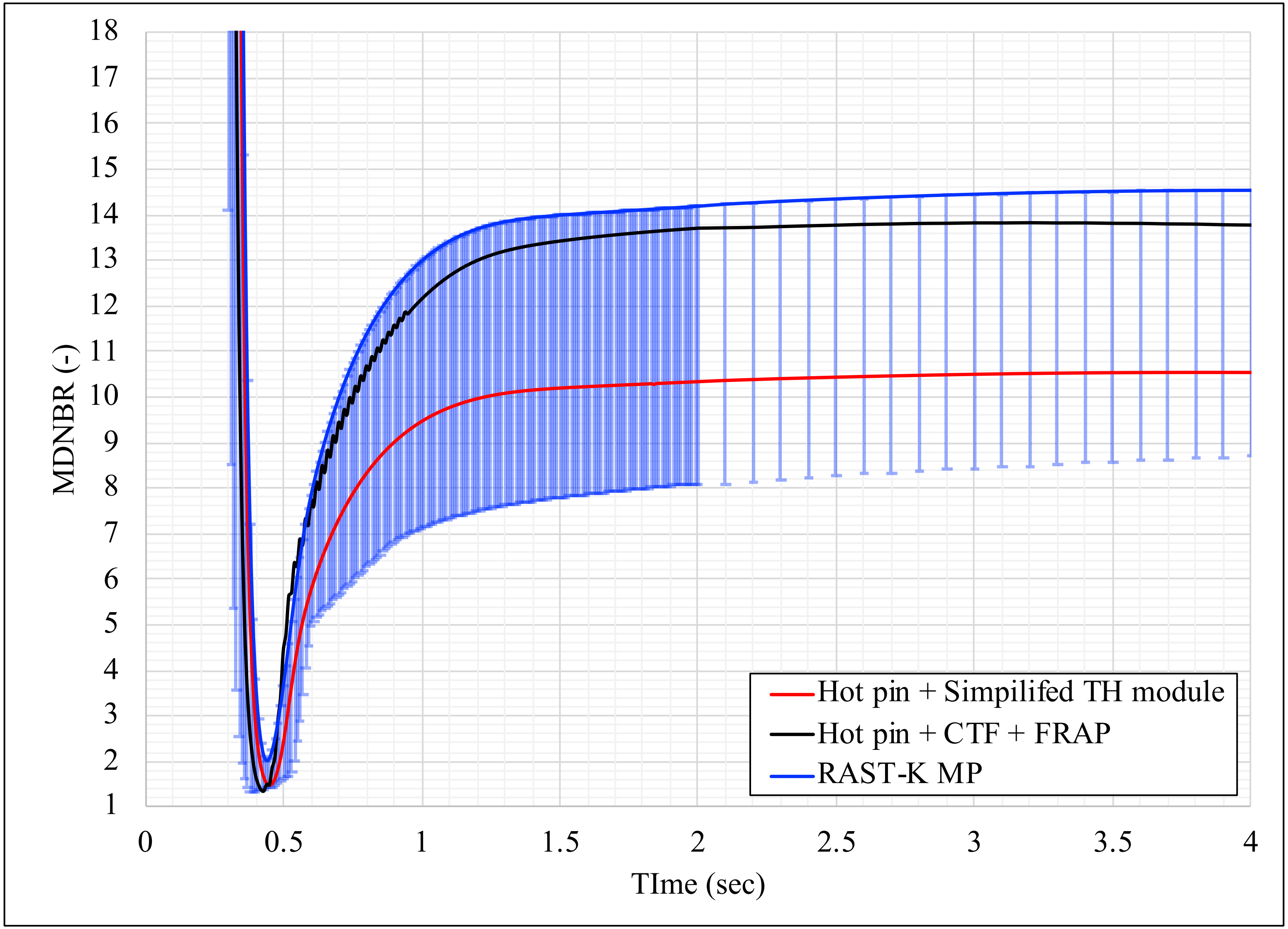
UQ for Transient Calculation: EOC HZP REA

- **Hot pin + Simplified TH vs. Hot pin + CTF + FRAP vs. MP**
  - **MDNBR**



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4. Conclusions

Development of BEPU Methodology using Multi Physics coupling code based on RAST-K

Conclusions

- **Multi-physics Coupling**
  - **Coupling with subchannel TH code, CTF**
  - **Coupling with fuel performance, FRAPCON & FRAPTRAN (via FRAPI)**
  - **Detail coupling parameter and algorithm is demonstrated**
  - **Perform multi-cycle depletion calculation**
    - Fuel temperature behavior during depletion is changed by considering detail fuel behavior such as TCD and dynamic gap conductance
    - It is observed that simplified TH module is enough for SS depletion
- **BEPU Methodology**
  - **Stochastic sampling method is employed**
    - Nuclear data & Input parameters perturbation
  - **UQ for depletion calculation**
    - Uncertainty of global parameters (CBC, ASI, Fq) is mainly coming from nuclear data pert
    - Perturbations of XS and input evenly contribute to uncertainty of TH-related outputs
  - **Perform UQ for REA transient simulations**
    - Tolerance limit of safety parameter can be observed by BEPU methodology

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