혁신형 SMR 핵설계 적용을 위한 상용원전 핵설계코드 개선 현황 (미래형원자로 노심설계 전산 코드체계 현황 및 개발 방향)

2025. 10. 29.

한전원자력연료 정위수

KEPCO NF

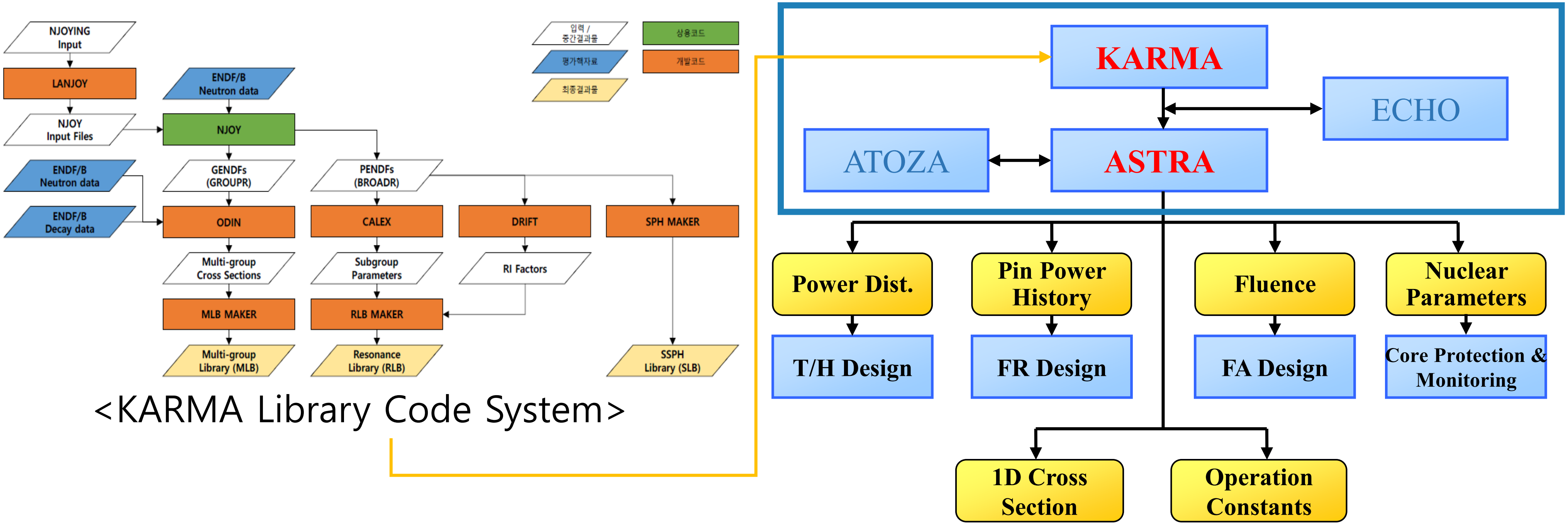
Contents

I

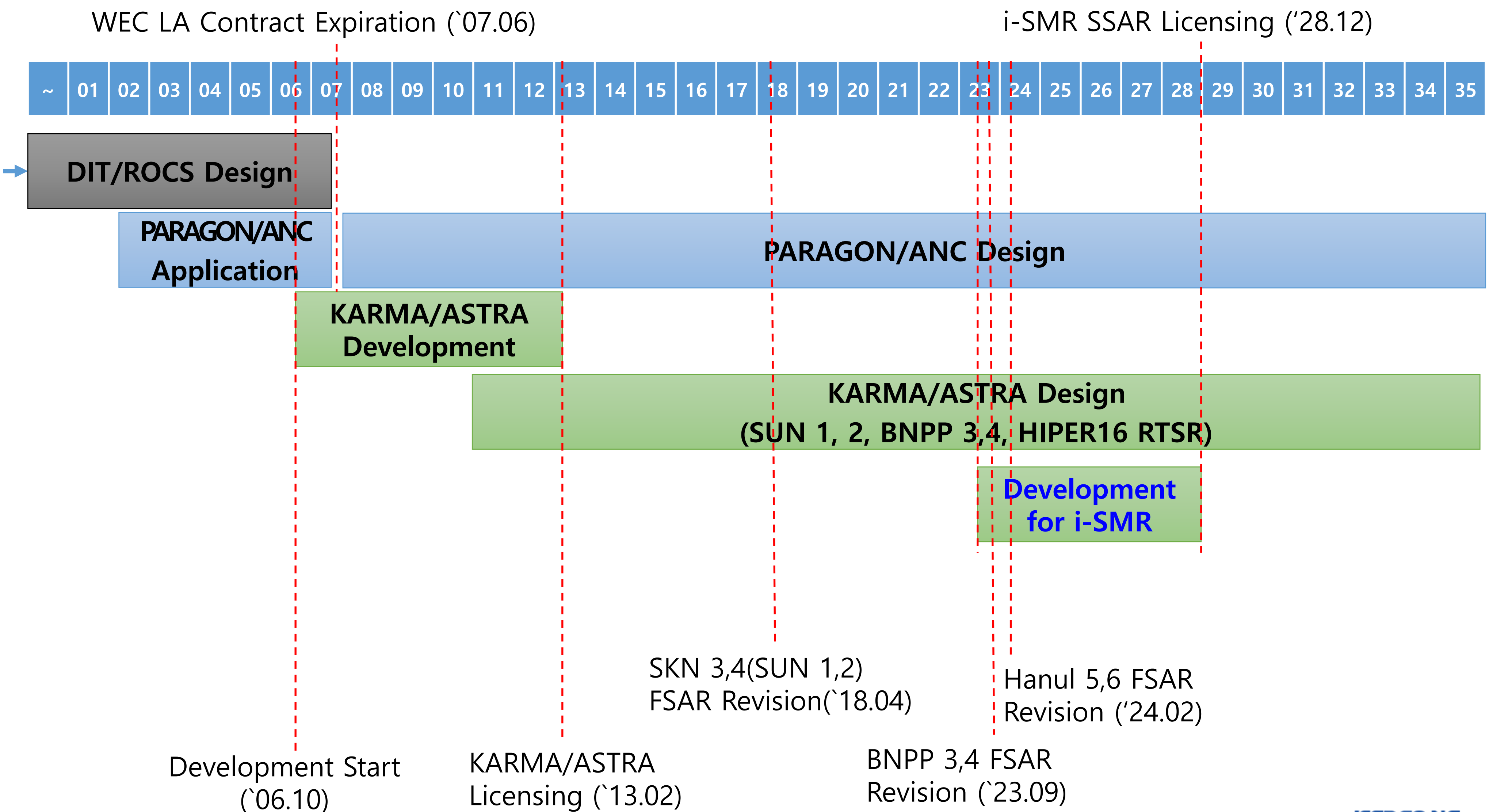
Background

- KNF ND Code System
- Design Characteristics of i-SMR
- Requirements for i-SMR Core Design

KNF Nuclear Design Code System



Milestone



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Revision History

	...	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	...
ASTRA					*1.0.2*	*1.1.0*	*1.3.0*	*1.4.0*	*1.4.1*	*1.4.2*		*1.4.3*			*1.4.4*	*1.4.5*	*1.5.0* *1.5.0_smr*	*1.5.1*	
KARMA		*1.1.1*				*1.2.3*	*1.2.4*	*1.2.5*	*1.2.6*			*1.2.7*					*1.2.7_smr*		
ATOZA					*1.0.2*	*1.1.0*	*1.2.0*	*1.3.0*		*1.4.0*	*1.5.0*	*1.5.1*		*1.5.2*	*1.5.3*		*1.5.3_smr*		
ECHO					*1.0.2*		*1.0.3*	*1.0.4*	*1.1.0*						*1.2.0*		*1.2.1*		
KARMA Lib.			*ENDF 6.8*														*ENDF 7.1*		
KARMA Lib. Code System						*LICOS(1)*							*LICOS(2)*						

Improvements of Core Design Code

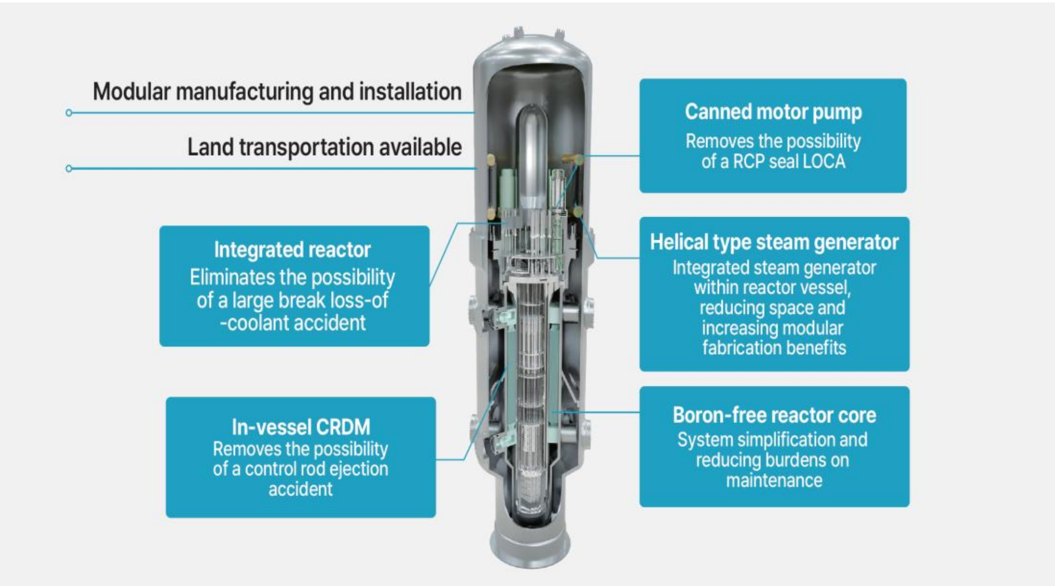
Improvements for PWR Core Design Code

- Mitigate the discrepancies between observed phenomena (measured data) and predictions
  - Xe induced Spectrum shift Effect (XSE)
  - Moderator Temperature induced Spectrum shift Effect (MTSE)
- Design data generation
  - Design input generation for other department analysis
  - Library generation for core monitoring

Challenges for the Development of i-SMR Core Design Code

- The design code was validated through comparison with measured data from 'the operating plants'.
- Lack of measurements → challenges in applying current validation schemes

i-SMR (innovative Small Modular Reactor)



Infinite cooling	Passive safety system that does not require operator action and power supply	Integrated control room	Integrated control room that can reduce operating costs through multi-module integrated control technology
In-vessel CRDM	In-vessel CRDM design to eliminate the possibilities of a control rod ejection accident	Innovative manufacturing technology	Reduction of manufacturing time through the introduction of innovative manufacturing technologies such as EBW
Innovative nuclear fuel	Nuclear fuel and burnable absorber for boron-free operation	Boron-free operation	Nuclear system simplification by eliminating the boron control system and reducing burdens on maintenance
Modularization	Modular technology to reduce construction time and increase economics	Automation	Improvement of the automation level of operation
Predictive diagnosis	Plant availability increase through O&M performance improvement	Connection with renewable energy	Flexible operation for compatibility with renewable energy

Electrical power	170 MWe (per Module)	Steam generator	Helical type
Total power	680 MWe (4 Modules)	Reactor coolant pump	4 (per Module)
Fuel assembly	UO_2 17×17	Safety system	Fully passive
Core damage frequency	≦1.0e-9 / MY	DC power	Non-safety
Construction cost	≦$3,500 / kWe	Design life	80 years
Neutron absorber	boron-free	Seismic design	0.5g
CRDM	In-vessel type	Construction time	24 months (Single Module)

Taken from i-SMR leaflet (https://www.ismr.or.kr)

Requirements for i-SMR Core Design

Boron-free Core

	Boron Core	Boron-free Core
Excess Reactivity Control	· Soluble Boron · Burnable Absorber	~~· Soluble Boron~~ · Burnable Absorber · Control Rod
Reactivity Control	· Soluble Boron · Control Rod	~~· Soluble Boron~~ · Control Rod

Innovative Burnable Absorber

- Requirements : Improved excess reactivity control
- Candidates : High-enriched (Gd-155 & 157) Gd_2O_3 (High Contents, Integrated BA, etc.)
- Phenomenon : Neutron spectrum hardening & Larger neutron flux gradient in fuel assembly

Rodded Operation

- Requirements : Rod position search for reactivity(criticality) control
- Phenomenon : Neutron spectrum hardening & Depletion of control rod absorber material

II

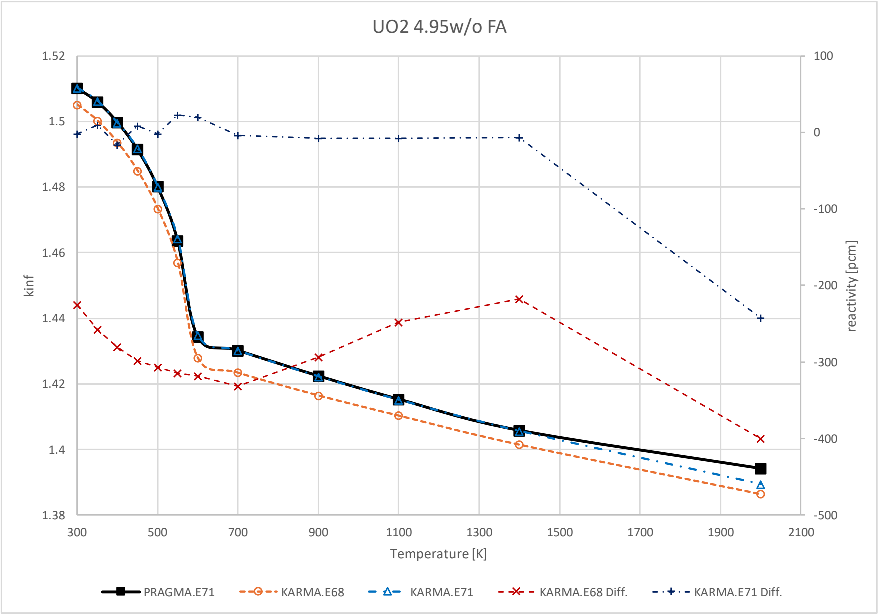
Improvements for i-SMR Design

- Improvements
- Verification & Validation
- Comparison Results

Improvements for i-SMR Core Design

KARMA Library

- 47group KARMA library based on ENDF/B-VII Rev.1
  - Apply recent & verified ENDF library (ENDF/B-VI.8 → ENDF/B-VII.1)
  - Improvement of calculation accuracy
  - Eliminating errors by different nuclear data in validation & verification phase by code comparison
  - KARMA library generation based on subgroup method
  - Apply library correction methodology developed by KHU



Improvements for i-SMR Core Design

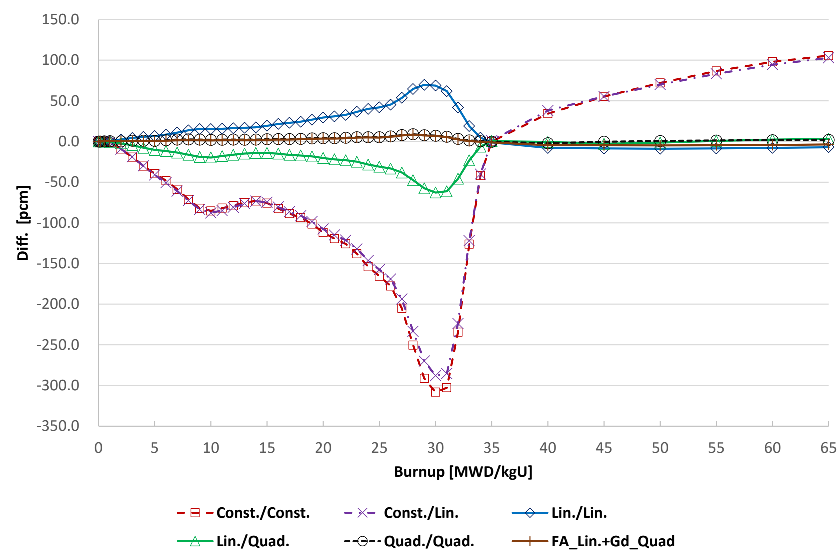
KARMA

Characteristics of BA for Boron-free core

- Required higher excess reactivity control : larger BA material number density causes neutron spectrum hardening → Impact on depletion calculation(delayed BA burnt out time) → Need improved accuracy
- Fine burnup interval : To improve BA material depletion accuracy → Need more computing power

Improved predictor-corrector for BA material depletion

- 2nd-ordered depletion array : Improved calculation accuracy
- Magnus integral : Improved depletion calculation efficiency



<Comparison of errors caused by coarse burnup interval>

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Improvements

KARMA

Improved Accuracy

FA ID	Gd-155&157 Enrichment [a/o]	Gd_2O_3 Contents [w/o]	# of Gd_2O_3 Rods	Bu Interval [MWd/kgU]	Max. Reactivity Diff. with CE/CM (0.1 MWd/kgU) [pcm]					
					CE/CM	CE/LI	LE/LI	LE/QI	**QE/QI**	QD
01	50	8.0	16	0.5	-84.7	-78.6	34.7	-5.7	**5.8**	5.7
				1.0	-308.3	-287.9	69.7	-62.8	**8.9**	8.5
				1.5	-624.2	-589.4	59.2	-189.0	**-14.3**	-15.4
02	50	8.0	20	0.5	-96.5	-89.5	39.4	-6.4	**6.6**	6.5
				1.0	-353.8	-331.3	78.7	-71.7	**10.0**	9.6
				1.5	-702.9	-658.2	67.3	-214.1	**-16.7**	-17.8
03	70	8.0	24	0.5	-69.0	-63.7	28.7	-4.6	**4.8**	4.7
				1.0	-253.3	-236.3	57.9	-51.2	**7.3**	6.7
				1.5	-502.8	-472.6	48.5	-151.3	**-11.0**	-12.3
04	70/NAT	8.0/2.0	20/4	0.5	-65.3	-60.5	27.0	-4.2	**4.4**	4.3
				1.0	-237.0	-222.4	55.5	-45.3	**6.8**	-7.4
				1.5	-489.1	-462.8	48.6	-142.5	**-5.6**	-7.2
05	70/70	8.0/0.3	24/4	0.5	-57.8	-52.9	24.9	-6.9	**4.0**	3.9
				1.0	-215.3	-199.8	54.8	-40.6	**-11.2**	-13.3
				1.5	-431.4	-404.6	56.6	-117.9	**-12.8**	-14.7

Improvements

KARMA

Improved Efficiency by Magnus Integral

- Problem : FAID 02, bu interval = 0.5 MWd/kgU

Algorithm	# of matrix calculations		Calculation Time **(before)** [ms] (Pred./Corr.)	Calculation Time **(after)** [ms] (Pred./Corr.)
	Before Magnus Integral (Pred./Corr.)	**After** Magnus Integral (Pred./Corr.)		
CE/CM	1 / 1		784 / 782	
CE/LI	1 / 5	1 / 2	800 / 3,294	800 / 1,410
LE/LI	5 / 5	2 / 2	3,292 / 3,276	1,423 / 1,402
LE/QI	5 /10	2 / 2	3,297 / 6,419	1,424 / 1,407
QE/QI	10 /10	2 / 2	6,591 / 6470	1,463 / 1,418
QD	5 / 10 (UO2) 10 / 10 (Gd2O3 + UO2)	2 / 2	4,573 / 4,534	1,433 / 1,405

- Note that effective cross-section calculation for resonant nuclide, depletion matrix organization, and matrix calculation takes 140ms, 12ms, and 640 ms in a depletion module, respectively.

Improvements

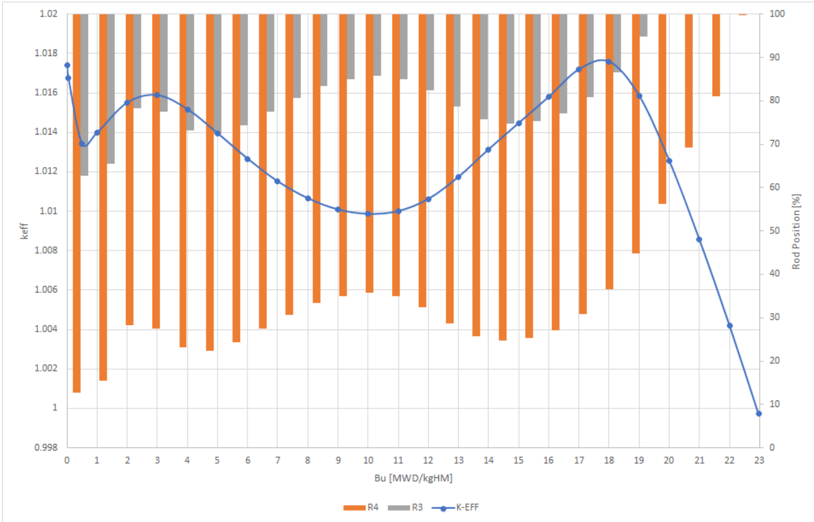
ASTRA

Rodded Operation for Boron-free Reactor

- Critical boron concentration → Critical rod position
- Rodded operation causes local neutron spectrum hardening → Impact on FA depletion
- Rodded operation causes depletion of absorber material (AIC) → Impact on reactivity

Functional Improvement of Critical Rod Position Search

- Add automatic EOC point search option by ARO point during depletion calculation
- Searched critical rod position is saved then reproduced in restart calculation

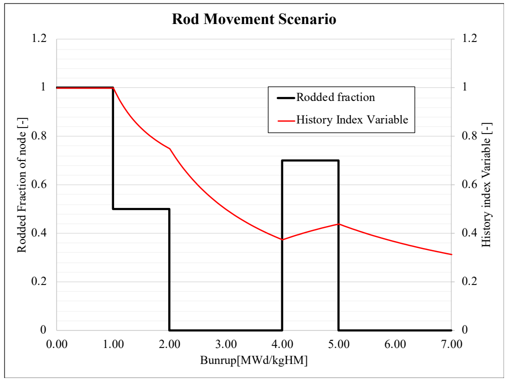


Improvements

ASTRA

Development of FA XS Feedback Method

- Combination of unrodded and rodded XS considering CR insertion history



$$\boldsymbol{h^k_{Hist}} = \frac{\sum_i^k (\boldsymbol{f^i_{Rodded}} \cdot \Delta \boldsymbol{BU_i})}{\sum_i^k (\Delta \boldsymbol{BU_i})}$$

$$\Sigma^k = h^k_{Hist} \cdot \Sigma^k_{Rodded\ base} + \left(1 - h^k_{Hist}\right) \cdot \Sigma^k_{Unrodded\ base}$$

Development of Control Rod Depletion Model

- Development of lumped isotope model of AIC

$$N_{eff} = N_{\mathrm{Ag107}} + N_{\mathrm{Ag109}} + N_{\mathrm{Cd113}} + N_{\mathrm{In113}} + N_{\mathrm{In115}}$$

$$\sigma_{eff} = \frac{1}{N_{eff}} \sum_{i=1}^{N_{CR}} \sigma_i N_i$$

- Control rod depletion quantity, $\beta(t) = 1 - \frac{N_{eff}(t)}{N_{eff}(0)}$, $0 \leq \beta(t) < 1$

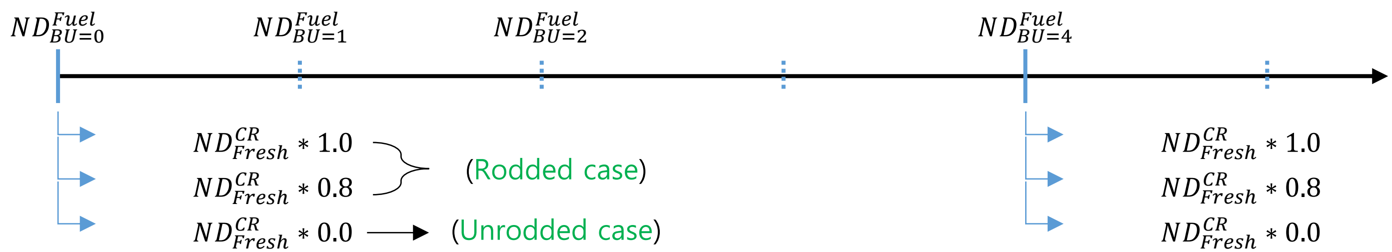
Improvements

ASTRA

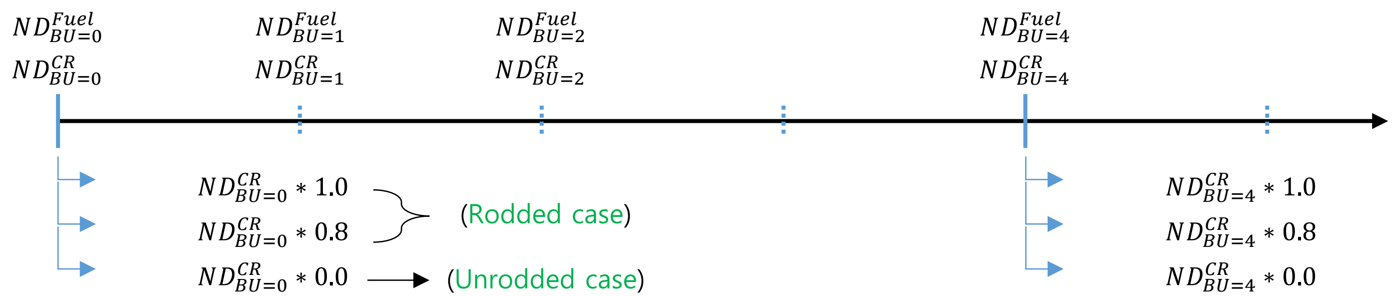
Development of XS Feedback Model Considering CR Depletion Effect

- New branch calculation matrix considering CR depletion effect

Unrodded Based Branch Calculation



Rodded Based Branch Calculation



- Modification of XS functionalization

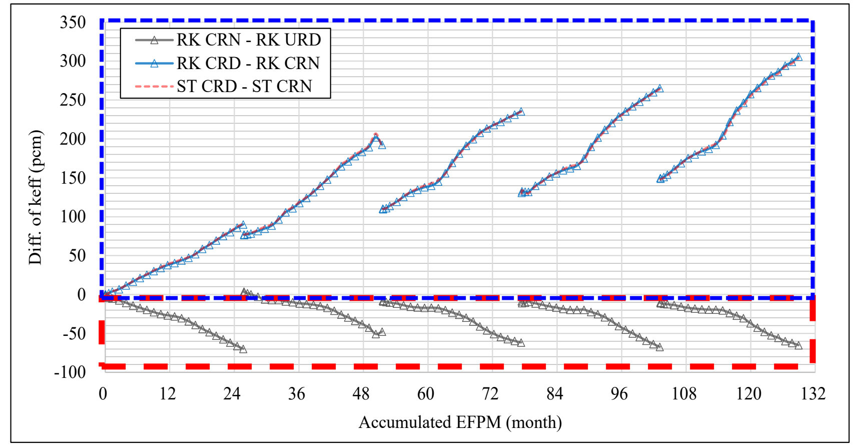
$$\sigma = f\left(BU, ppm, \sqrt{T_{fuel}}, T_{mod}, CR(\beta)\right)$$

Improvements

ASTRA

Impact on Core Reactivity

- Impact of XS feedback Method : -70pcm
- Impact of CR depletion : +300 pcm



Impact on Local Power Distribution

- Increased RMS error for FA power dist.
- Improved accuracy around rodded FA (-7.73% to -0.67%)
- Improved accuracy peaking factor (3.74% to 2.68% for Fq error)

Rodded FA | Peak FA

BOC			RMSE =	2.52%
0.623	0.620	0.787	1.279	1.146
0.659	0.646	0.804	1.263	1.148
-5.38%	-4.07%	-2.18%	1.27%	-0.19%
0.619	0.457	0.982	1.286	0.985
0.646	0.495	0.973	1.267	0.975
-4.17%	-7.73%	0.98%	1.48%	0.98%
0.784	0.980	1.176	1.237	0.796
0.804	0.974	1.165	1.211	0.804
-2.50%	0.67%	0.96%	2.15%	-0.98%
1.268	1.281	1.239	1.066	
1.263	1.273	1.213	1.069	
0.43%	0.66%	2.11%	-0.26%	
1.134	0.984	0.806		RK URD
1.148	0.986	0.818		ST3D
-1.21%	-0.29%	-1.39%		Diff. (%)

BOC			RMSE =	1.34%
0.656	0.650	0.808	1.273	1.134
0.659	0.646	0.804	1.263	1.148
-0.51%	0.64%	0.49%	0.81%	-1.20%
0.650	0.492	0.991	1.277	0.972
0.646	0.495	0.973	1.267	0.975
0.53%	-0.67%	1.94%	0.81%	-0.30%
0.806	0.990	1.173	1.227	0.787
0.804	0.974	1.165	1.211	0.804
0.17%	1.62%	0.67%	1.32%	-2.13%
1.263	1.273	1.229	1.054	
1.263	1.273	1.213	1.069	
0.00%	0.01%	1.28%	-1.40%	
1.123	0.971	0.796		RK CRD
1.148	0.986	0.818		ST3D
-2.18%	-1.55%	-2.59%		Diff. (%)

Verification & Validation

Validation & Verification for Nuclear Design Application

- Verification : Verify implementations
- Validation : Verify the physical adequacy
  - Validation activity include the comparison with (1) analytic solutions, (2) physical tests, (3) results from other code (RG 1.168, NUREG/CR-6463, IEEE Std 1012, etc.)
- Uncertainty Evaluation : Compare measurement and predict

Challenges of Application for Boron-free Core Design

- No measurement data from boron-free core (operation or tests)
- No experience and data for long-term rodded operation
- Need to establish the V&V system for inexperienced cores
  - Validation activity by comparing (reference) code results is suggested

Verification & Validation

PRAGMA (Power Reactor Analysis using GPU-based Monte Carlo Algorithm)

- Developed by SNU-KHNP

PRAGMA

  - Program language: CUDA C++
  - Implementing acceleration methods (CMFD & Ramp-up) → decrease calculations of in-active cycles & increase of tracking rate using GPU → able to use large amount of (~10^8) particles

- Verify Reliability through Benchmark Problems
  - APR1400 Benchmark (BOC), BEAVRS Benchmark (2 cycles depletion)

- Reference Results Generation for Major Nuclear Design Parameters
  - Core Reactivity, Iso-Thermal Coefficient, Power Coefficient, Fuel Temperature Coefficient, CR worth, etc.
  - Implemented Critical Rod Position Search Function

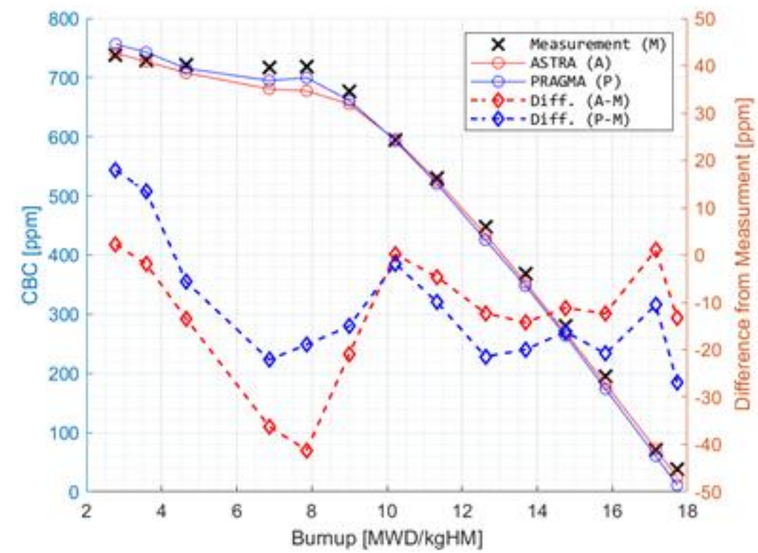
Verification & Validation

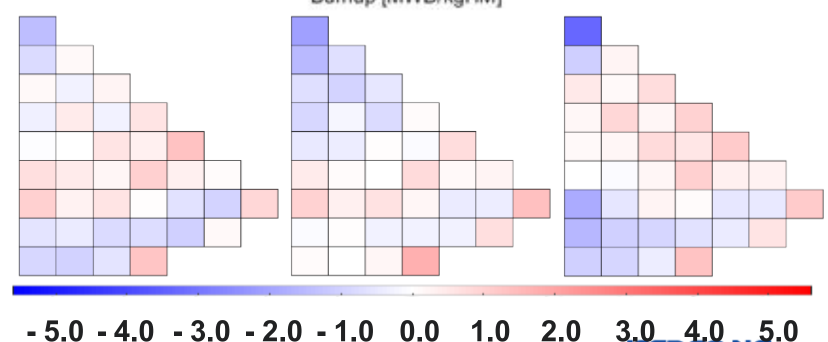
V&V for PRAGMA

- Applicability Evaluation : SUN unit1 cycle 1 LPPT & Depletion Calculation

Parameters	Meas. (M)	PRAGMA(P)	Diff. (M-P)	Test Criteria
ITC [pcm/°C]	-3.1175	-4.7167	1.5992	±9
IBW [ppm/pcm]	9.315E-2	9.200E-2	0.115E-2	±1.5E-2
CBC @ HZP [ppm]	1163.273	1192.050	-28.777	±50
CBC @ 100%P	759	749.28	9.72	
개별제어봉가 R5	232.25	257.08	-25.49	±15% or 100pcm
개별제어봉가 R4	419.00	417.20	0.05	
개별제어봉가 R3	630.00	661.66	-36.07	
개별제어봉가 R2	883.00	906.23	-31.52	
개별제어봉가 R1	1143.00	1195.13	-66.61	
개별제어봉가 A	2346.70	2197.89	-4.24%	±10%
개별제어봉가 B	2438.93	2388.57	0.33%	

2D FA Power Distribution			
Power Level	20%	50%	80%
RMS Error [%]	0.70	0.74	0.96
Max. Error [%]	2.06	2.98	4.81





Comparison Result

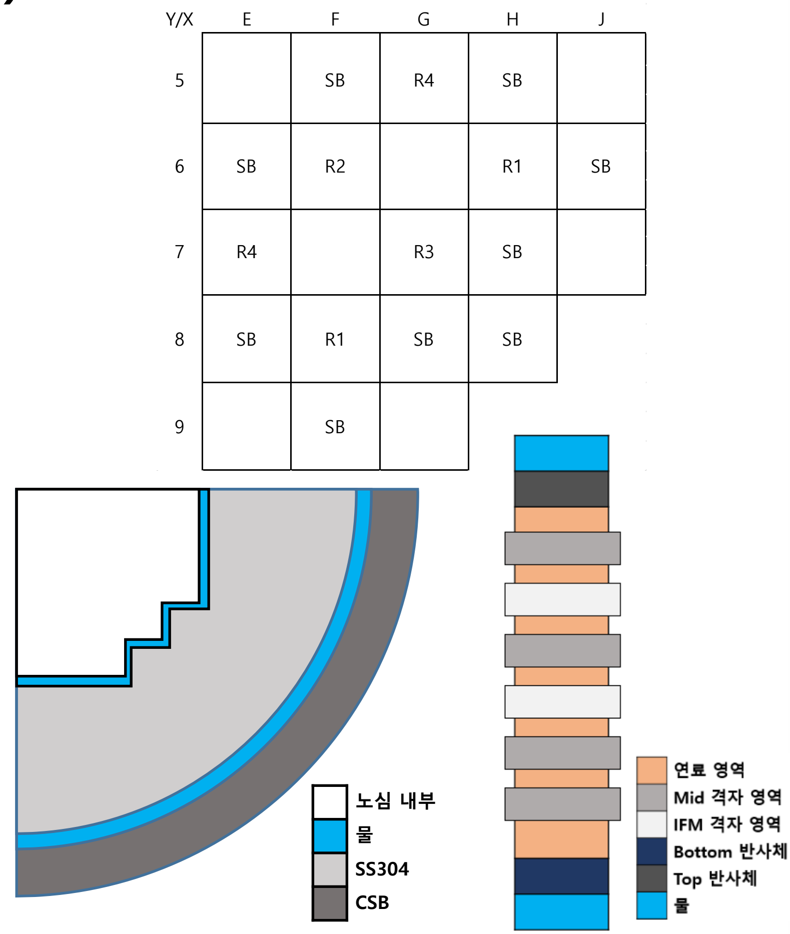
Comparison for i-SMR Core Calculation (1/4 model)

i-SMR model specification

Power	520 MWth	HFP Tin/Tout	286°C/323°C
# of FAs	69	Pressure	15MPa
Active Height	240 cm	CR type	28-finger
FA type/array	UO2/17x17 square pitch	CR Material	Regulating: AIC Shutdown: B_4C
U enrichment	< 5wt%	Refueling cycle	24 month
Grid	2IFM/3Mid	Batch	2 batch

PRAGMA Calculation Condition

Condition	Value
Particles per cycle	100,000,000
In-active/Active cycles	20/40
CMFD acceleration	Used
Library	ENDF/B-VII.1 (450K/500K/550K/..../1800K, total 16)



<몬테칼로 코드를 이용한 i-SMR 모델링>

III

Summary

- Summary and Future Work

Summary

Improvement for i-SMR Boron-free Core Design

- KARMA Library based on ENDF/B-VII.1
  - Eliminate errors due to differences in nuclear data when comparing with references
  - Improvement of calculation accuracy
- KARMA Functional Improvement
  - Increase calculation accuracy for BA loaded FA depletion through predictor/corrector improvement
  - Increase calculation efficiency for depletion module through application of Magnus integral
- ASTRA Functional Improvement
  - Functional improvement of critical rod position search
  - Development of XS feedback model for control rod insertion and depletion of control rod material

Summary

Improvement for i-SMR Boron-free Core Design

V&V System Establishment

- Validation by comparing Monte-Carlo Code, PRAGMA
- Verification and validation of PRAGMA with benchmark problems (APR1400, BEAVRS)
- Validation of PRAGMA with measurement data

Comparison between PRAGMA and ASTRA

- Power distributions are compared at Cycle 1 BOC, then RMS errors of 2D power distribution for ARO and rod insertion conditions (R4, R4+R3, R4+R3+R2, R4+R3+R2+R1) are less than 3.1%
- Rod worths are compared and the maximum difference both total and individual are under -1.2%.
- Depletion results of ARO and CRP are compared and maximum difference is under 200 pcm

감사합니다