Neutronic Analysis of an Uprated Soluble-Boron-Free ATOM Core Design Based on the Centrally-Shielded Burnable Absorber

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Introduction: Advantages and Challenges

- ❑ **The rise of Small Modular Reactors (SMRs)**
  - Integrated and compact module (modularity) -> Flexibility and safety
  - Reduced capital cost -> Economics
  - Smaller core -> Bigger Leakage -> Lower fuel utilization (discharge burn-up)
- ❑ **Soluble-Boron-Free (SBF) Core**
  - Minimization of Chemical and Volume Control System -> Simplified design
  - Reduced corrosion and radioactivity level in primary loop
  - Always Negative Moderator Temperature Coefficient (MTC) -> Enhanced safety
    - Elimination of boron-related reactivity accidents
    - Neutron moderation can be optimized further
    - The MTC is strongly negative
    - Challenge for reactor start-up and shutdown -> control rod worth
    - Core is sensitive to the moderator temperature and density fluctuations
    - Heavily bottom skewed axial power distribution-> Axial power oscillation
    - Need an innovative excess reactivity control beside the control rods
  - Lower neutron economy as the standard FA is optimized for soluble-boron condition.

Introduction: KAIST SBF SMR

❑ **KAIST SMR, named ATOM (450 MWth), is a high-performance SBF core that could resolve the aforementioned challenges by adopting:**

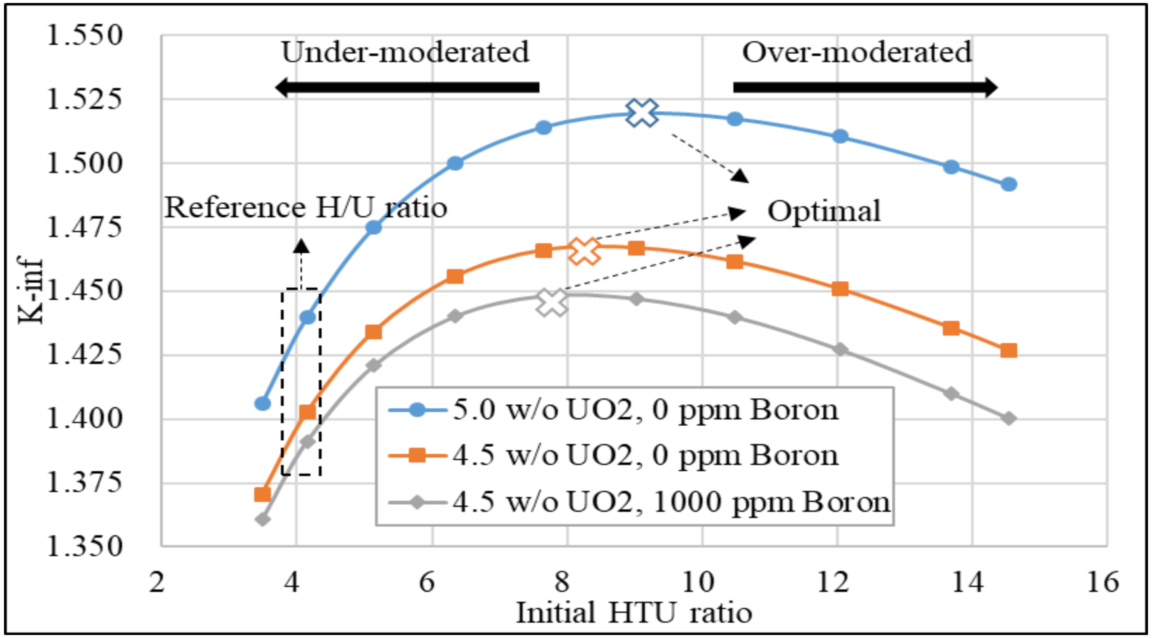
- Truly-optimized PWR (TOP) FA design
  - Improves the fuel utilization
  - Reduces temperature defect
- 3-D advanced BA design: centrally-shielded BA (Axially zoned)
  - Achieves a small excess reactivity -> less than 1,000 pcm
  - Minimizes power peaking
  - Stable axial power distribution
- Introducing extended shutdown CEA
  - Practical checker-board CR pattern with only 54% rodded FA

Introduction: Main Objectives

- **In this study, the ATOM core power is uprated from 450 to 540 MWth**
  - The core active height is increased to 2.4 m
    - Increases the fuel inventory
    - Might be prone to the axial power oscillation
- **Effective and simplified 3-D burnable absorber (BA) design**
  - Axially uniform CSBA
- **Incorporates a small amount of Erbia into the certain fuel rods**
  - Minimizes the local peaking factor
  - Helps to manage the early excess reactivity
- **Axial fuel enrichment zoning**
  - Simple axial zoning for practical application to tackle the axial power oscillation
- **The whole calculations were performed utilizing the Serpent 2 Monte Carlo code with ENDF/B-VII.1 library**

540 MWth ATOM Core Design

- **Truly Optimized PWR (TOP) lattice**



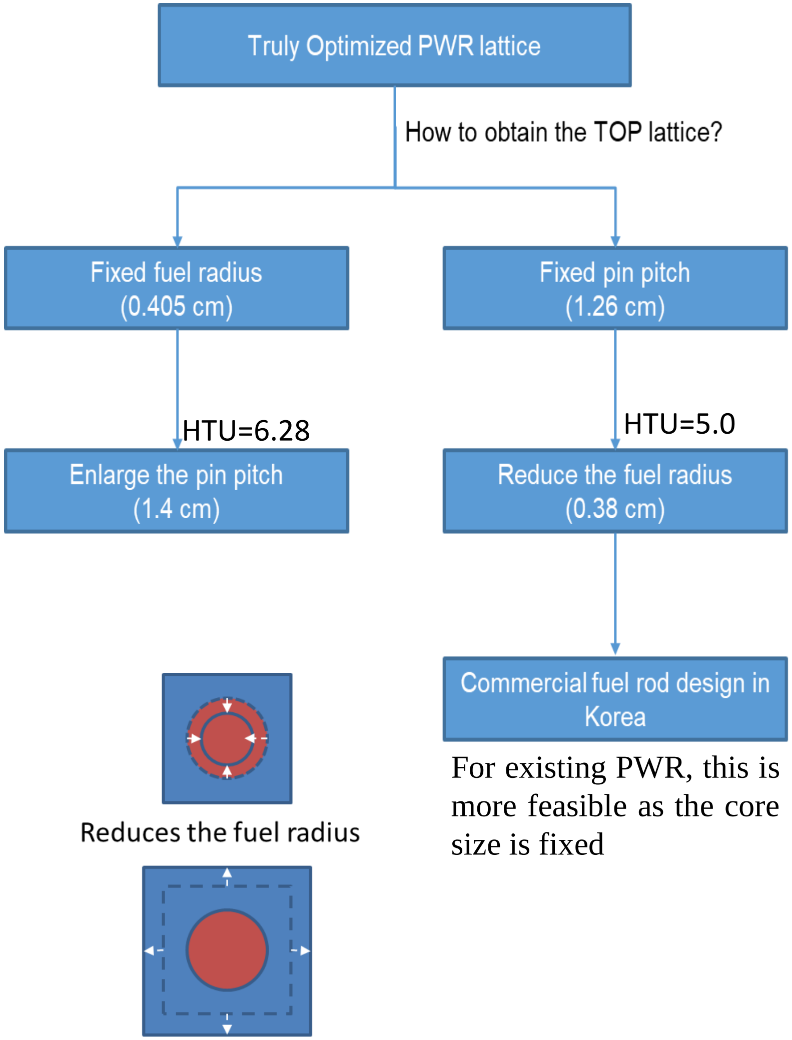
Infinite multiplication factor respect to Hydrogen to Uranium (HTU) value

- **Clearly “under-moderated” in the standard PWR FA**
  - Optimized under soluble boron -> to assure negative MTC
  - Moderation capacity reduces with the presence of soluble boron, while it enhances with a higher fuel enrichment
  - Far from optimal for the SBF core

Ha, et al., Truly-optimized PWR lattice for innovative soluble-boron-free small modular reactor. Sci Rep 11, 12891 (2021).

540 MWth ATOM Core Design

- ☐ **Truly Optimized PWR (TOP) lattice**
  - **A higher moderation is strongly favored to maximize the potential of the SBF SMR.**
  - Clearly better neutron economy
  - Sufficiently negative and similar MTC throughout the reactor operation
  - Favorable MTC at high burnup → Smaller temperature defect → Higher shutdown margin at the Cold-Zero-Power (CZP) condition
  - Smaller pressure drop:
    - Slightly lower CHF -> Need a comprehensive TH analysis
  - A higher HTU ratio can be applicable for SBF system and a higher fuel enrichment, within an enrichment limitation of 4.95%, is preferable.
- ☐ **TOP lattice design can be achieved by either:**
  - Increasing the pin pitch for a given fuel rod diameter;
  - Reducing the fuel rod diameter for a given pitch.



Truly Optimized PWR lattice

How to obtain the TOP lattice?

Fixed fuel radius (0.405 cm)

HTU=6.28

Enlarge the pin pitch (1.4 cm)

Fixed pin pitch (1.26 cm)

HTU=5.0

Reduce the fuel radius (0.38 cm)

Commercial fuel rod design in Korea

For existing PWR, this is more feasible as the core size is fixed

Reduces the fuel radius

Increases the pin pitch

540 MWth ATOM Core Design

❑ Truly Optimized PWR (TOP) lattice

- MTC comparison between the standard FA with the TOP FA.
- The calculation is performed:
  - Serpent 2 Monte Carlo code with ENDF/B-VII.1 library
  - Under SBF condition without any BAs

FA design	H/U	0 MWd/kgU		40 MWd/kgU		MTC changes (pcm/K)
		MTC (pcm/K)	Uncertainty (pcm/K)	MTC (pcm/K)	Uncertainty (pcm/K)	
Standard PWR FA	4.10	**-30.39**	0.32	**-40.55**	0.43	**-10.16**
TOP 1.26/0.38	5.00	**-24.90**	0.30	**-29.56**	0.40	**-4.66**
TOP 1.40/0.41	6.28	**-18.29**	0.28	**-21.63**	0.38	**-3.35**

- The standard FA design has the most negative MTC and most significant MTC changes during the depletion
- Both TOP FA designs have sufficiently negative MTC and minor MTC changes during the depletion.

540 MWth ATOM Core Design

❑ Centrally-Shielded Burnable Absorber

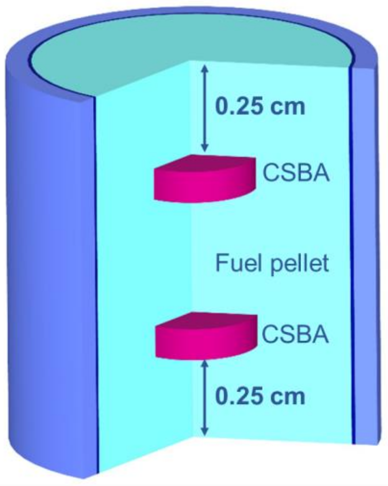
- Classified as integral BA design
- Gd_2O_3 cylindrical pellets load into fuel region
- Depletion rate is easily managed by adjusting the height-to-diameter (HTD) ratio
- Less residual reactivity penalty
- After sintering process it is found that the crystal structure of the Gadolinia is changed from cubic into monoclinic
  - The density is changed from 7.4 to 8.33 g/cm^3

❑ Erbia admixed into the fuel pellet

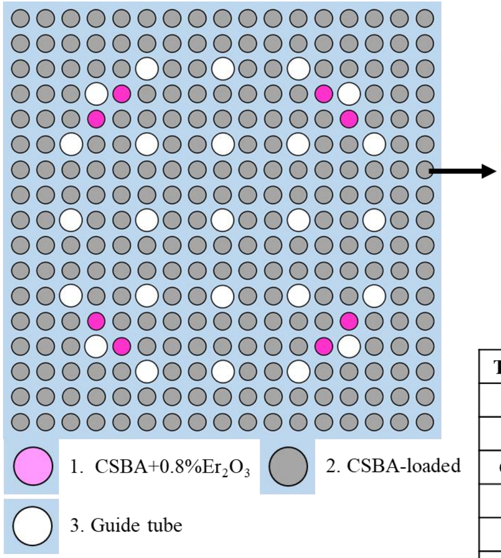
- A small amount (0.8%) of Erbia is admixed into the fuel pellet
- To minimize the local pin power peaking and reduce the early excess reactivity

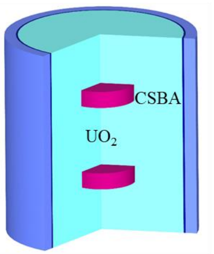
❑ TOP design:

- Smaller fuel radius with 0.38 cm.
- 14% less fuel inventory than that for standard PWR fuel
- Provide less negative moderator coefficient (MTC)
- Applicable to current commercial PWRs



Fuel pellet with 2-cylinders CSBA



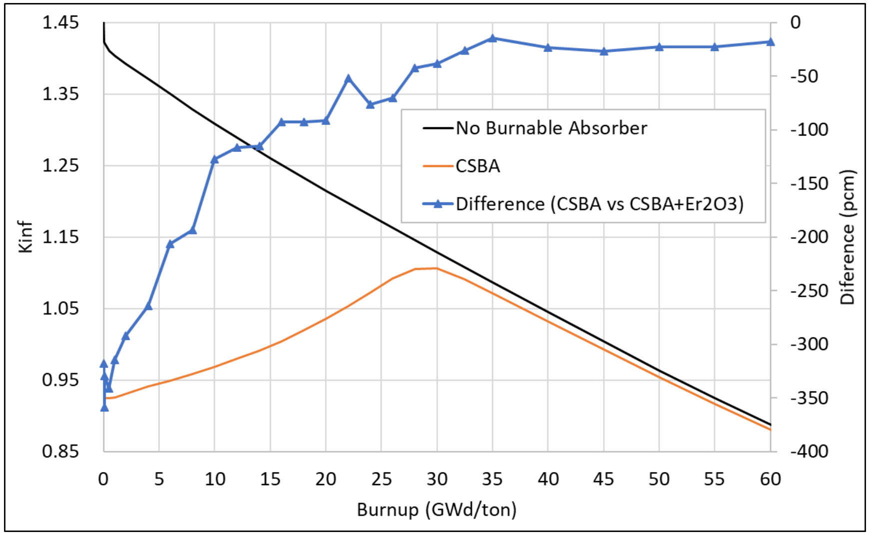


CSBA-loaded fuel pellet

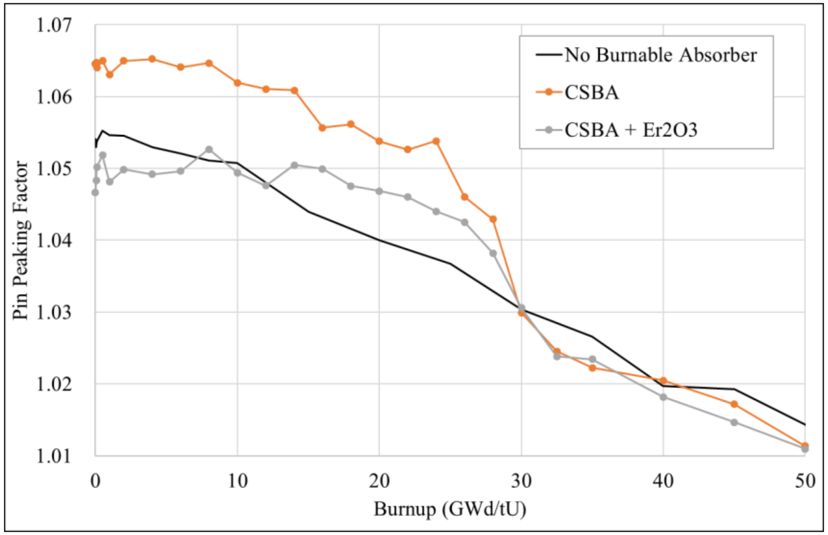
TOP FA parameter	Value
Fuel pellet radius	0.38 cm
Helium gap	0.00915cm
Cladding thickness	0.0573 cm
Pin pitch	1.2623 cm
HTU ratio	5.0
FA pitch	21.6038 cm

540 MWth ATOM Core Design

- **FA analysis**
  - Impacts of CSBA and Er2O3 on both reactivity and local power peaking



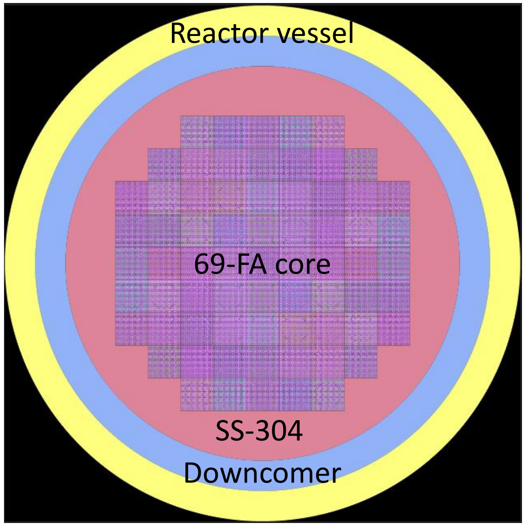
The Impacts of CSBA and Er2O3 on Reactivity

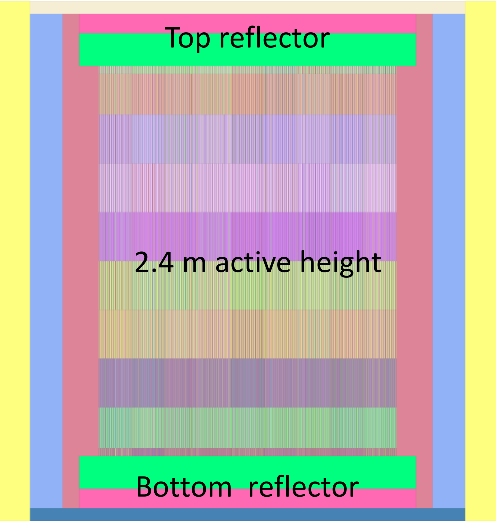


The Impacts of CSBA and Er2O3 on Local Power Peaking

540 MWth ATOM Core Design

Parameters	Value
Thermal power	540 MWth
Fuel Shuffling	Two-batch
Number of fresh FA	35
Fuel materials, enrichment	UO_2, 4.95 w/o
Radial reflectors	SS-304
Axial active core height	240 cm
BA design	CSBA
BA material	Monoclinic Gd_2O_3
Gd_2O_3 theoretical density	8.33 g/cc
Gd_2O_3 density	7.40 g/cc (89% TD)
FA type, total number of FA	17 x 17, 69
Fuel pellet radius	0.38 cm
Reactivity swing (target)	1,000 pcm
Pin pitch (cm)	1.26 cm
Inlet & Outlet coolant Ts	295.7/323^{0}C

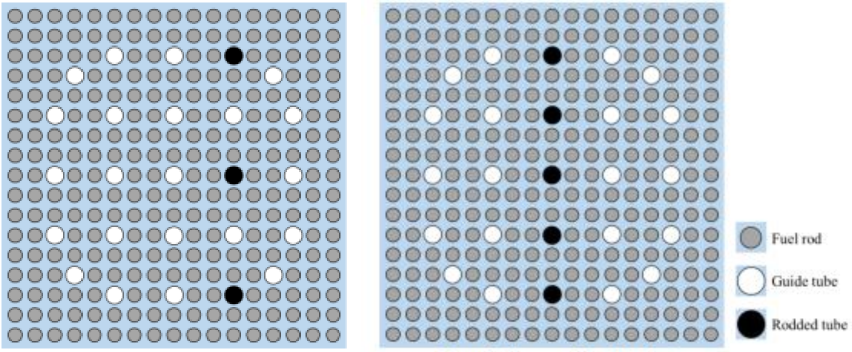




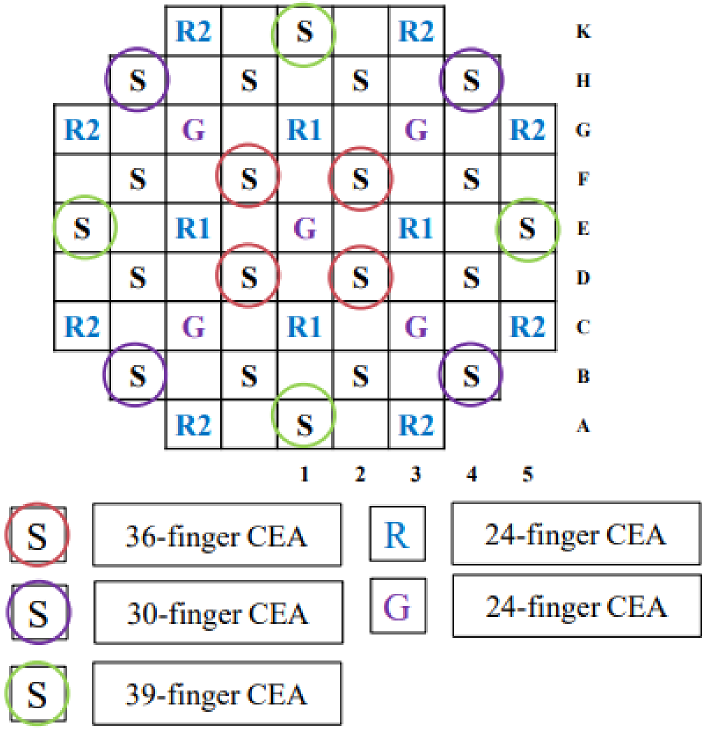
540 MWth ATOM Core Design

❑ Checker-board CR pattern

- Gray rod
  - designed to have a similar rod worth to the reactivity swing
  - The criticality is solely obtained by GR bank.
  - Minimize local power distortion.
- R1 and R2 are for power control and hot-zero-power shutdown
  - R2 for power control, while R1+R2 for hot-zero-power condition
- Several shutdown CEAs have extended fingers to their neighbouring FAs



Partially rodded FA 1 Partially rodded FA 2

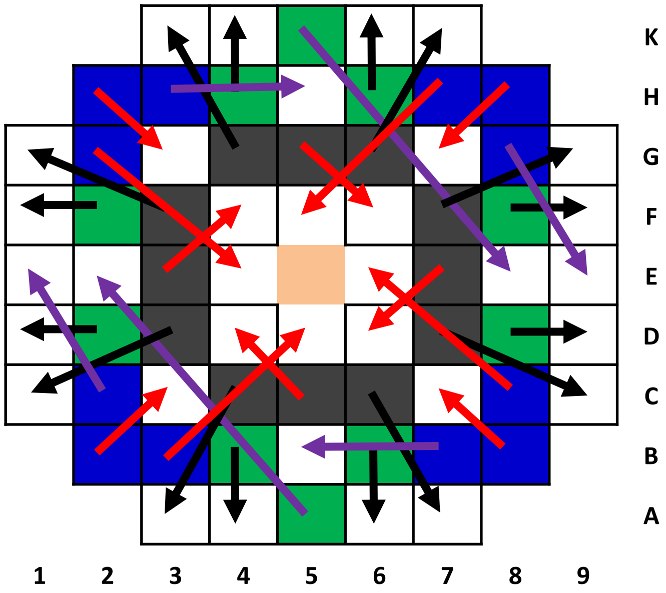


S	Shutdown Bank	20
R1	Regulating Bank (Nat. B_4C)	4
R2	Regulating Bank (50%B_4C)	8
G	Gray Bank (SS-clad Mn)	5
Total		37

THE ATOM CR DESIGN AND PATTERN

540 MWth ATOM Core Design

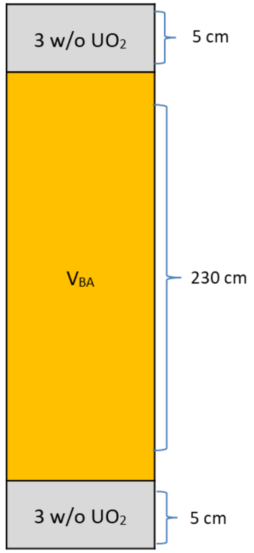
- **Fuel-shuffling scheme and zoning**



Fuel Shuffling and Zoning

🟧	Special Fresh FA (3.0 w/o UO_2)
⬛	Fresh FA Zone I (4.95 w/o UO_2)
🟩	Fresh FA Zone II (4.95 w/o UO_2)
🟦	Fresh FA Zone III (4.95 w/o UO_2)
⬜	Burned FA

Axial BA loading



Radial zone-wise CSBA parameter

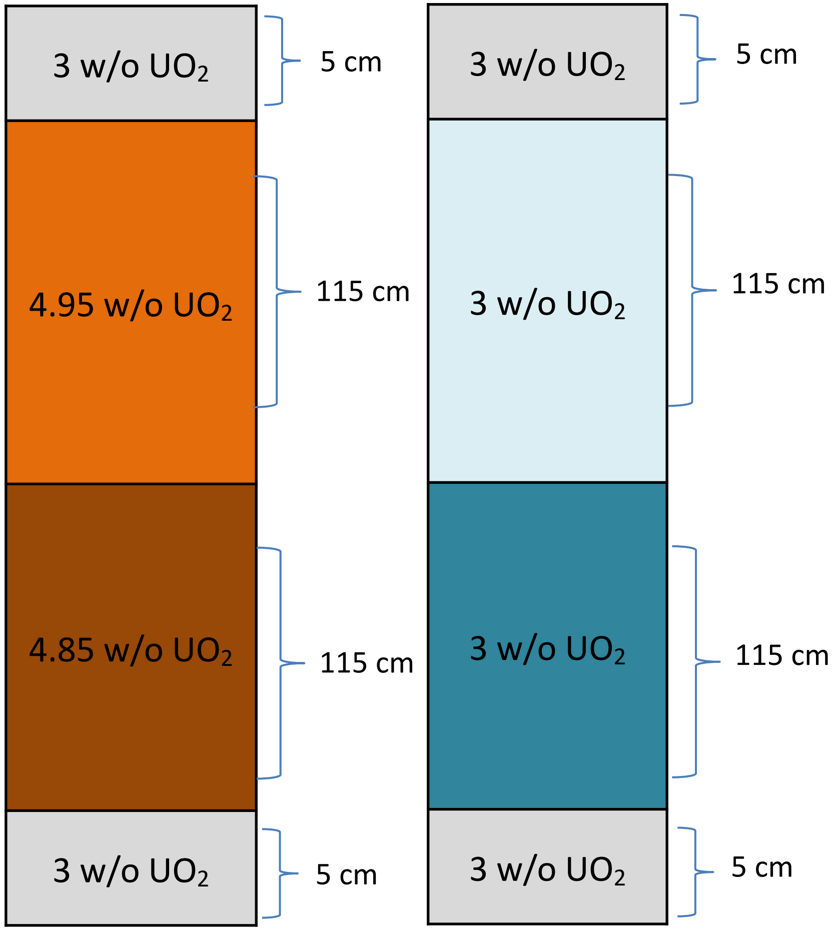
Parameter	Zone			
	I	II	III	Center
Diameter (mm)	3.30	2.66	2.42	2.66
Height (mm)	0.79	0.88	0.80	0.88
H/D ratio	0.28	0.33	0.33	0.33

Fuel Shuffling Scheme

Zone I		Zone II		Zone III	
Fresh	Burned	Fresh	Burned	Fresh	Burned
C2	A3	B2	A2	B3	H1
D3	C5	D4	D5	B4	C3
E3	D2	F4	F5	C4	E2
F3	G5	H2	K2	G4	E5
G1	F2	K1	E4	H3	F1
G2	K3			H4	G3

540 MWth ATOM Core Design

- **Axial fuel enrichment zoning**



Zone I,II,III

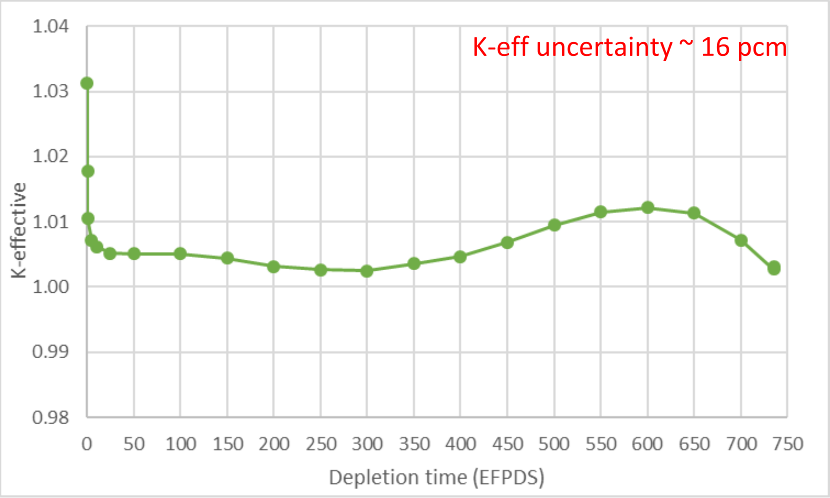
Zone center

Axial fuel enrichment zoning

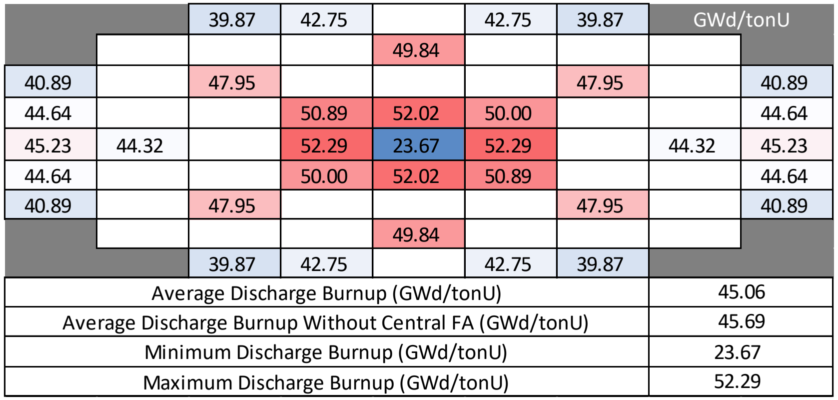
Axial position (cm)	Zone			
	I	II	III	Center
195-200	3 w/o	3 w/o	3 w/o	3 w/o
100-195	4.95 w/o	4.95 w/o	4.95 w/o	3 w/o
5-100	4.85 w/o	4.85 w/o	4.85 w/o	3 w/o
0-5	3 w/o	3 w/o	3 w/o	3 w/o

540 MWth ATOM Core Design

- **Two-year cycle length (730 EFPDs) is achieved, while the excess reactivity is around 1,200 pcm**
  - It is also maintained at least 300 pcm excess reactivity during the cycle to overcome the power drop transient.
  - It is demonstrated that cylindrical CSBA combined with a small amount of Erbia is effective to control the excess reactivity for the whole reactor operation.
- **The average discharge burnup is comparable to the three-batch PWRs**
  - Effective fuel utilization due to the TOP concept and maximum allowable 4.95% U enrichment.
  - Minimal discharge BU is about 39.87 GWd/tU.
  - APR1400 average discharge burnup: 46.5 GWd/tU* while the ATOM core average discharge burnup: 45.69 GWd/tU



K_{eff} evolution in the eq. cycle



		39.87	42.75		42.75	39.87	GWd/tonU	
				49.84				
40.89		47.95				47.95		40.89
44.64			50.89	52.02	50.00			44.64
45.23	44.32		52.29	23.67	52.29		44.32	45.23
44.64			50.00	52.02	50.89			44.64
40.89		47.95				47.95		40.89
				49.84				
		39.87	42.75		42.75	39.87		

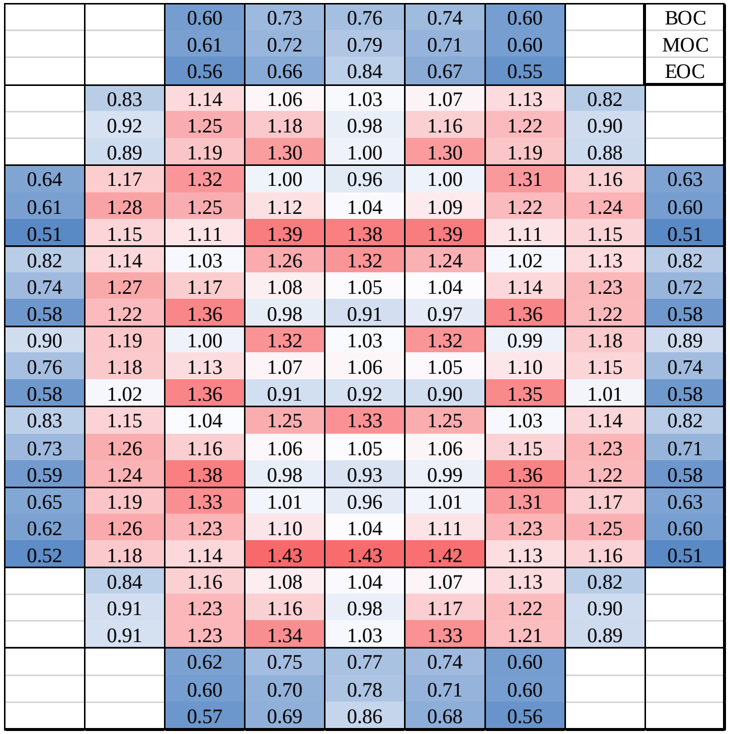
Average Discharge Burnup (GWd/tonU)	45.06
Average Discharge Burnup Without Central FA (GWd/tonU)	45.69
Minimum Discharge Burnup (GWd/tonU)	23.67
Maximum Discharge Burnup (GWd/tonU)	52.29

Discharge burnup mapping

Status Report – APR1400 (KEPCO E&C/KHNP) KOREA. IAEA ARIS 2020/05/15

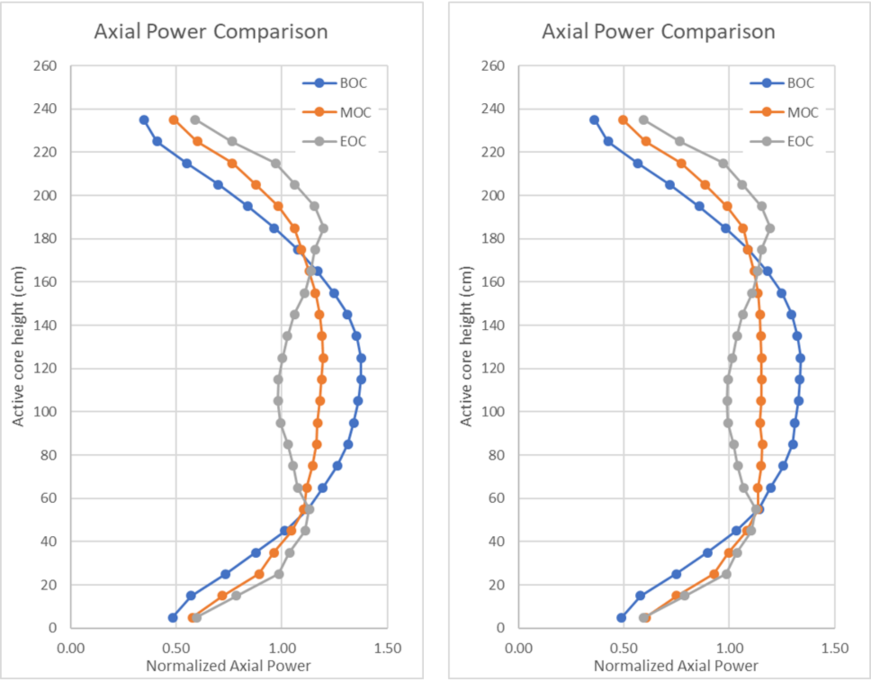
540 MWth ATOM Core Design

- **Both radial and axial peaking factors are relatively small < 1.43**
  - The associated uncertainties for the axial and radial power are 0.14% and 0.22% respectively
- **A minor power oscillation is observed between even and odd cycles**



		0.60	0.73	0.76	0.74	0.60		BOC
		0.61	0.72	0.79	0.71	0.60		MOC
		0.56	0.66	0.84	0.67	0.55		EOC
	0.83	1.14	1.06	1.03	1.07	1.13	0.82	
	0.92	1.25	1.18	0.98	1.16	1.22	0.90	
	0.89	1.19	1.30	1.00	1.30	1.19	0.88	
0.64	1.17	1.32	1.00	0.96	1.00	1.31	1.16	0.63
0.61	1.28	1.25	1.12	1.04	1.09	1.22	1.24	0.60
0.51	1.15	1.11	1.39	1.38	1.39	1.11	1.15	0.51
0.82	1.14	1.03	1.26	1.32	1.24	1.02	1.13	0.82
0.74	1.27	1.17	1.08	1.05	1.04	1.14	1.23	0.72
0.58	1.22	1.36	0.98	0.91	0.97	1.36	1.22	0.58
0.90	1.19	1.00	1.32	1.03	1.32	0.99	1.18	0.89
0.76	1.18	1.13	1.07	1.06	1.05	1.10	1.15	0.74
0.58	1.02	1.36	0.91	0.92	0.90	1.35	1.01	0.58
0.83	1.15	1.04	1.25	1.33	1.25	1.03	1.14	0.82
0.73	1.26	1.16	1.06	1.05	1.06	1.15	1.23	0.71
0.59	1.24	1.38	0.98	0.93	0.99	1.36	1.22	0.58
0.65	1.19	1.33	1.01	0.96	1.01	1.31	1.17	0.63
0.62	1.26	1.23	1.10	1.04	1.11	1.23	1.25	0.60
0.52	1.18	1.14	1.43	1.43	1.42	1.13	1.16	0.51
	0.84	1.16	1.08	1.04	1.07	1.13	0.82	
	0.91	1.23	1.16	0.98	1.17	1.22	0.90	
	0.91	1.23	1.34	1.03	1.33	1.21	0.89	
		0.62	0.75	0.77	0.74	0.60		
		0.60	0.70	0.78	0.71	0.60		
		0.57	0.69	0.86	0.68	0.56		

Radial assembly-wise power profile



Odd cycle

Even cycle

Axial core-average power profile

540 MWth ATOM Core Design

Temperature coefficient analysis

  - Temperature defect: reactivity difference between Hot-Full-Power (HFP) and Cold–Zero-Power (CZP)
  - Power defect: reactivity difference between HFP and Hot-Zero-Power (HZP)
  - The MTC is evaluated at $\Delta T = 20$ K
  - The FTC is evaluated at $\Delta T = 80$ K

- **Both FTC and MTC are sufficiently negative and slightly varied between BOC and EOC**
  - Slightly varied MTC during nominal operation is advantageous for the power control (less CR movement)
- **In any case, the cold shutdown is guaranteed**
  - For ARI case, the requirement is that the Keff < 0.95
  - For N-1 case, the requirement is that the Keff < 0.99

Temperature Coefficients

Cases	BOC	EOC*
HFP-MTC (pcm/K)	-53.19±0.42	-66.40±0.37
HFP-FTC (pcm/K)	-2.66±0.10	-2.97±0.09
Temperature defect (pcm)	-6,700±8	-7,701±7
Power defect (pcm)	909±8	-985±7

Cold Shutdown Evaluation

Case	BOC		EOC*	
	K-eff	Rod worth	K-eff	Rod worth
ARO	1.10023		1.11538	
ARI	0.91057	18,919	0.91500	19,802
N-1 (E1)	0.91123	18,847	0.91602	19,691
N-1 (E3)	0.91522	18,411	0.93902	17,212
N-1 (F2)	0.97603	11,978	0.96113	14,884
N-1 (F4)	0.94957	14,726	0.98256	12,678
N-1 (G3)	0.95533	14,121	0.94541	16,534
N-1 (H2)	0.94937	14,748	0.98053	12,886

*Rod worth unit = pcm, *at 600 EFPD*

Conclusions and Future Works

- **Conclusions**
  - The neutronic performance of the uprated ATOM Core has been investigated.
  - The combination of CSBA and Er_2O_3 successfully suppressed the excess reactivity to 1200 pcm
  - The core could achieve a two-year cycle length, having a comparable discharge burnup to PWRs, with a two-batch fuel management.
  - The proposed checker-board CR pattern guaranteed the cold shutdown for the ATOM core at any conditions.
- **Future Works**
  - TH-coupled rodded depletion analysis will be conducted to ensure a more robust and practical application
  - Load-follow analysis of the proposed core design also will be performed

Thank you for your attention