A Monte Carlo-Diffusion Two-step Analysis of a Soluble-Boron-Free SMR Using Centrally-Shielded Burnable Absorber

May 18th, 2018

Xuan Ha Nguyen and Yonghee Kim*

Department of Nuclear & Quantum Engineering
Korea Advanced Institute of Science & Technology

Presented at the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 16-18, 2018

Presentation Outline

1. **Introduction**
2. **Centrally-Shielded Burnable Absorber (CSBA) Design**
3. **A Monte Carlo-Diffusion Two-Step Analysis**
4. **Soluble Boron Free (SBF) Small Modular Reactor (SMR)**
5. **Numerical Results**
6. **Conclusion and Future Works**

Motivation for SBF PWR

- **Next generation PWRs requirements**
  - **Enhanced Power Maneuvering (Load-Following)**
  - **Increased level of autonomous operation**
  - **Less dependence on active controllers**
  - **High-intelligent control**

  → Soluble-Boron-Free Design is desirable

- **Spatially uniform response with soluble boron. Nevertheless:**
  - **Complicated and expensive de-borate operation and maintenance**
  - **Slow core reactivity control response (not suitable for power maneuvering)**
  - **'Less' negative or even slightly positive MTC at CZP condition with CBC**
  - **Boric acid-induced corrosion on structural materials**

SBF Operation Requirements

- **In an SBF system, almost all excess fuel reactivity at HFP is to be compensated by burnable absorbers**
  - Reactivity swing thought the cycle should be < 1000 pcm and > 400 pcm

- **SBF ATOM core should also be designed to survive a sudden power drop in a big transient**
  - It is required to survive a 100%-to-20% power drop in a large PWR core
  - Smaller value for SMR core due to the less power density (We aim to maintain 400~500 pcm)

Centrally-Shielded Burnable Absorber (CSBA) Design

CSBA design concept:

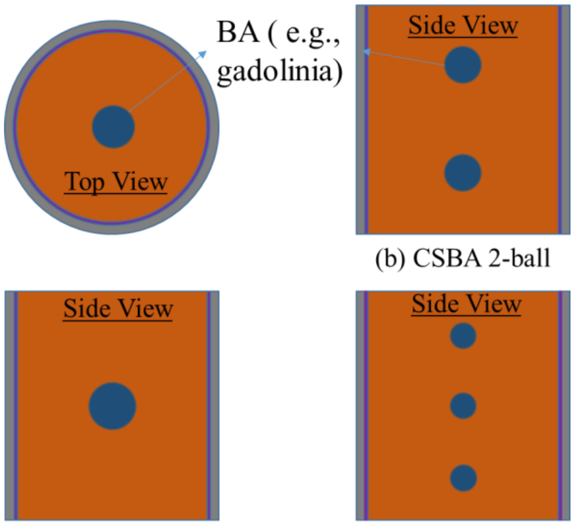
- CSBA is a UO_2 fuel pellet with BA balls in its centerline.

CSBA advantages:

- Flexibility of spatial self-shielding of BA to achieve slower burnup rate with gadolinia sphere
- Achievable for many design variants (Good room of optimization)
- No degradation of thermal and/or mechanical properties
- CSBA is confined within the fuel even if it melt down

CSBA disadvantages:

- Less fuel inventory → shorter cycle length



(b) CSBA 2-ball

(a) CSBA 1-ball

(c) CSBA 3-ball

CSBA-loaded Fuel Pellet

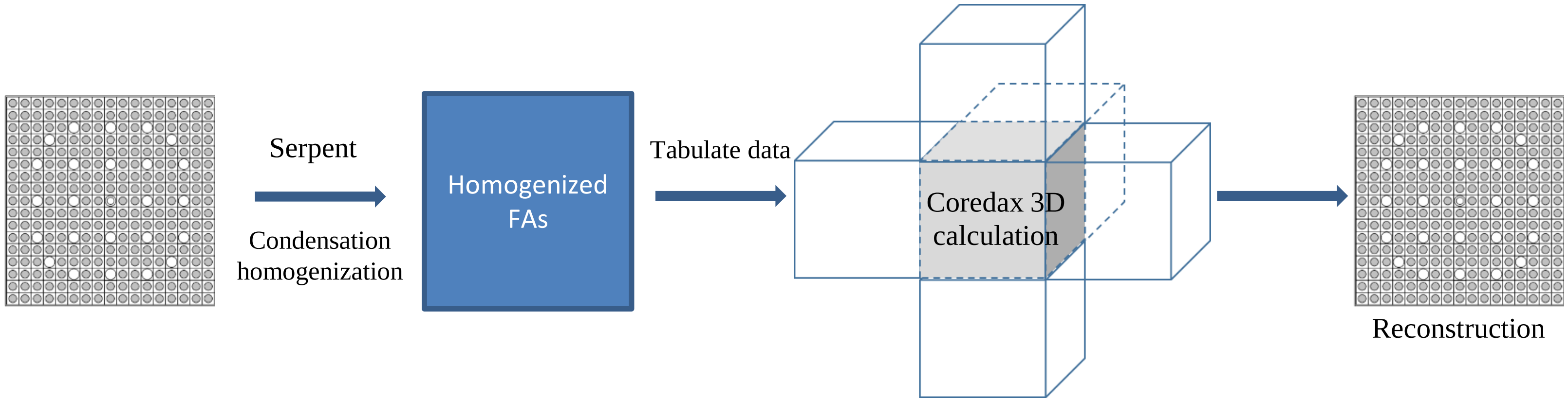
A Monte Carlo-Diffusion Two-Step Analysis (1)

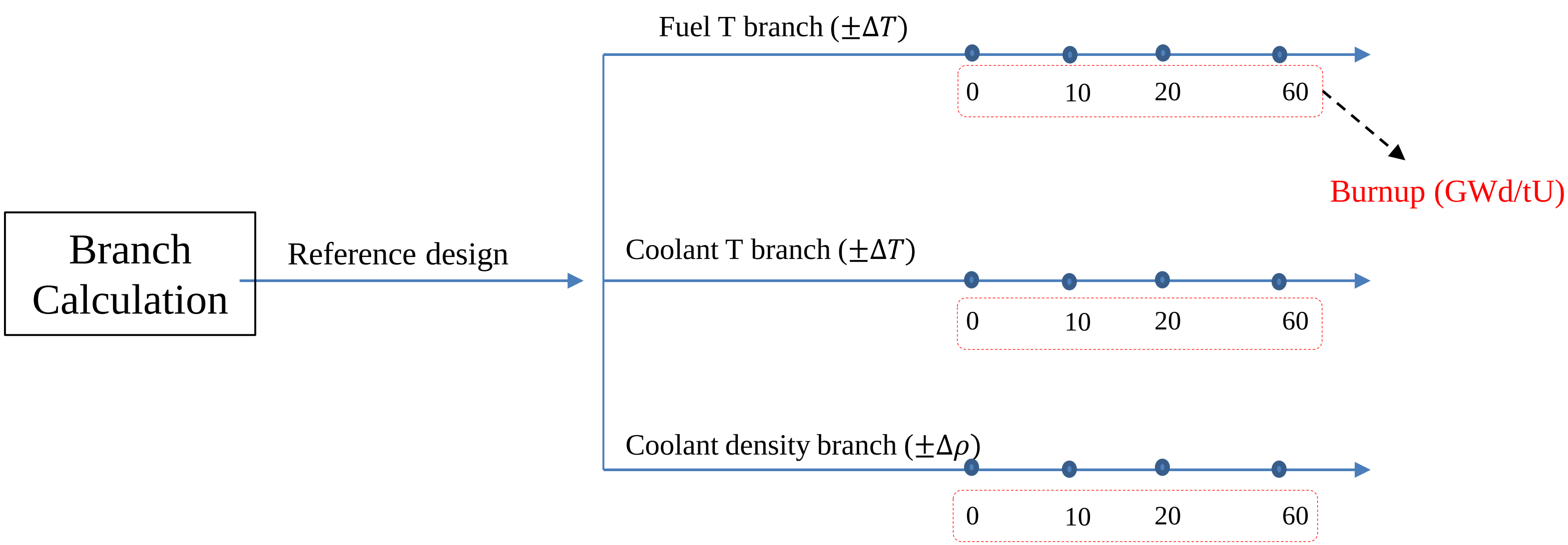
Advantage of the two-step procedure (Serpent*-COREDAX** analysis)

- Monte Carlo Serpent is capable of handling complicated geometry of CSBA for spatial homogenization process.
  - Without major approximations: isotope interference, spatial self-shielding, lattice resonance approximation
  - Accurate model heterogeneous lattice → reference solution
- Efficient and accurate lattice branch depletion calculation with on-the-fly cross-sectional temperature treatment
- The reference solution for the problem can be provided by Serpent
- COREDAX* code offers 3-D coupled thermal-hydraulics and neutronic calculation, which is necessary for SBF SMR analysis (highly negative CTC)

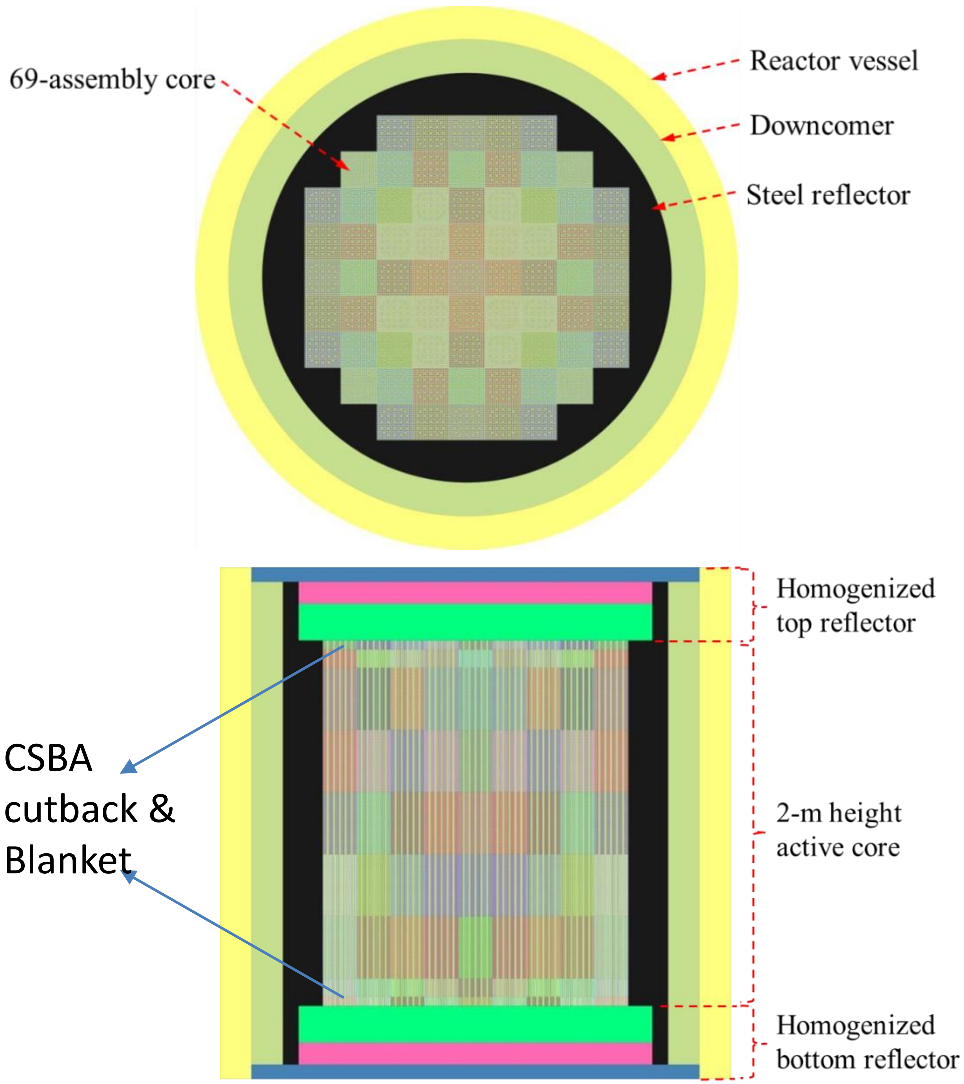
** J. Leppänen, et al, "The Serpent Monte Carlo code: status, development and applications in 2013," Annals of Nuclear Engergy, vol. 82, pp. 142-150, 2015.
** B. Cho, S. Yuk, N. Z. Cho and Y. Kim, "User's manual for the rectangular three-dimensional diffusion nodal code COREDAX-2 version 1.8," KAIST, Daejeon, ROK, 2016

A Monte Carlo-Diffusion Two-Step Analysis (2)





Soluble-Boron-Free ATOM (SMR) Core



Serpent model of the ATOM core

Parameters	Target Value	Unit
Thermal power	450	MWt
Active core height	200	cm
Equivalent diameter	201.6	cm
Power density	26.0	W/gU
Cycle length	>36	month
Fuel loading	Single-batch	
FA type	17 x 17	
Number of FAs	69	
Fuel materials	UO_2	
Fuel enrichment (max)	4.95	w/o
Reactivity swing*	< 1,000 > 400	pcm
Boron concentration	0	ppm

* ((max k_{eff} - 1)/max k_{eff}) x 10^5 [pcm]

CSBA Design: Variants, Ball Radius and Loading Schemes

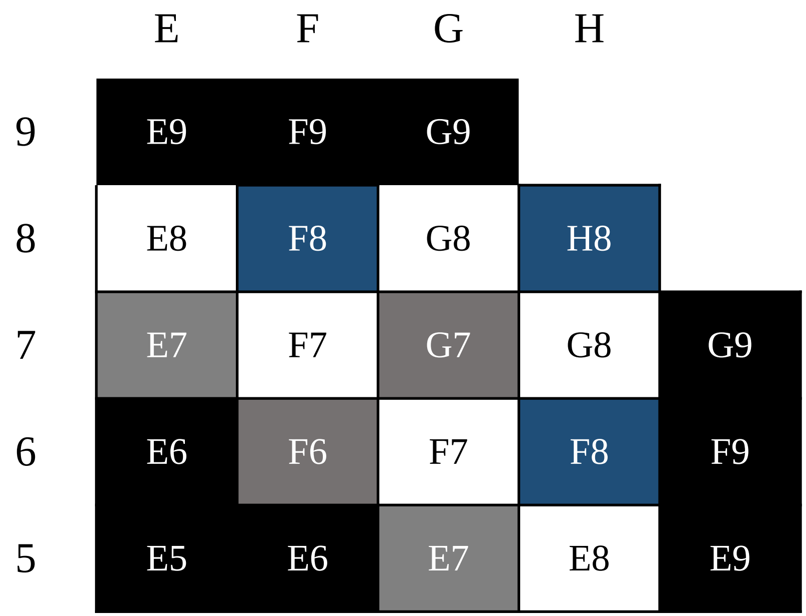
	E	F	G	H	
9	E9	F9	G9		
8	E8	F8	G8	H8	
7	E7	F7	G7	G8	G9
6	E6	F6	F7	F8	F9
5	E5	E6	E7	E8	E9

A Quarter of ATOM core

Zone	Enrichment
Zone A	4.95 w/o U
Zone B	4.95 w/o U
Zone C	4.95 w/o U

Case	Parameters	CSBA Design (variant and ball radius, r)		
		Zone A	Zone B	Zone C
Reference CSBA only	CSBA type Ball radius Mass fraction (Gd2O3 / UO2)	1-ball, r = 1.690 mm 0.0269	2-ball, r = 1.260 mm 0.0221	3-ball, r = 0.700 mm 0.0055

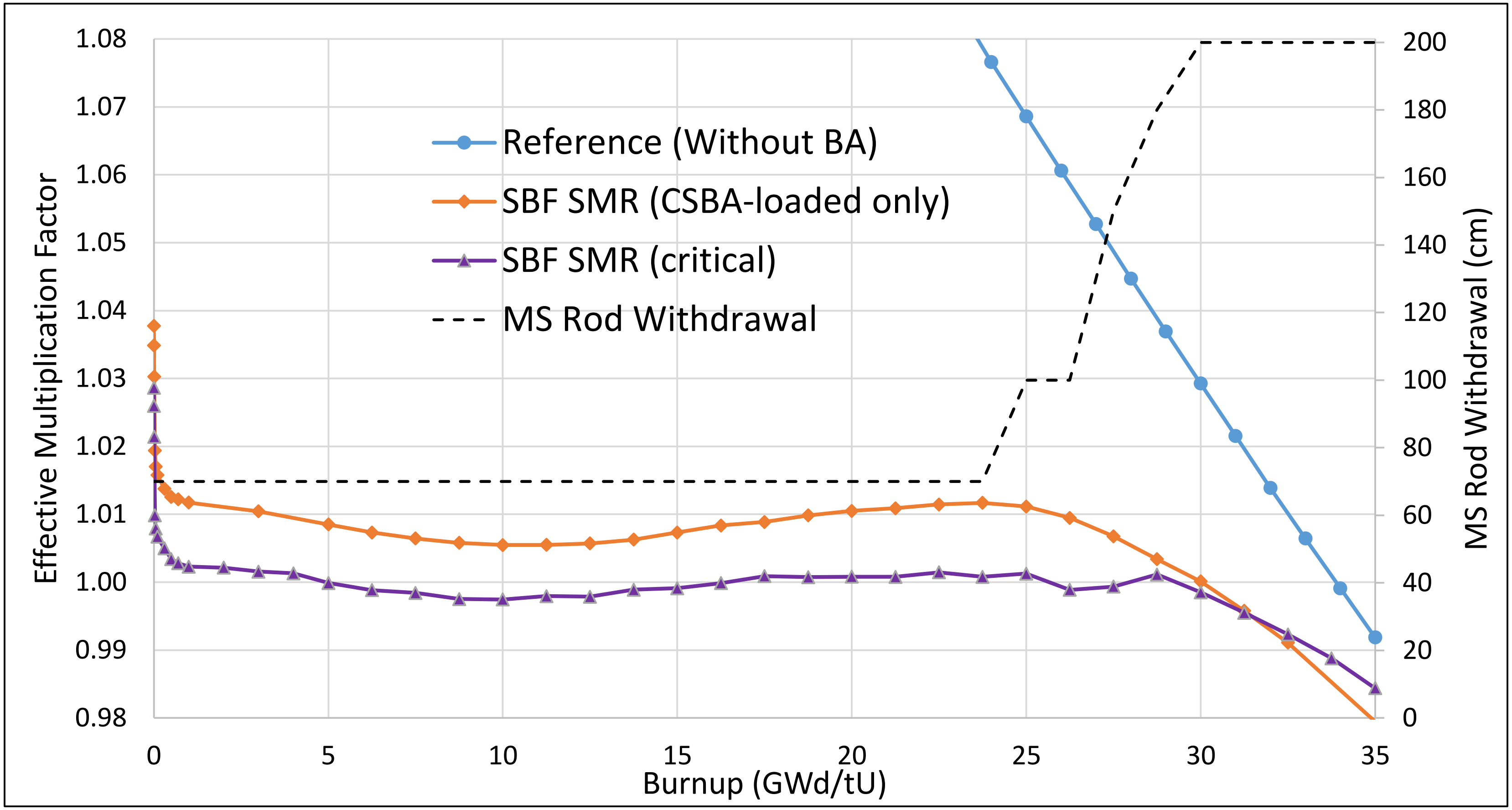
Control Rod Design with A Checker-board Pattern



Color	Legend	Total number
	Shutdown bank 95% B_{10}-enriched B4C	17
	MS bank Hf-doped stainless steel	12
	Regulating Bank natural B4C	12

The use of mechanical shim rods to obtain the core criticality

Critical CSBA-loaded SMR with Mechanical Shim (MS) Rod Insertion



Case	Rho Swing (pcm)	Minimal Rho (pcm)	Discharged Burnup (GWd/tU)	Uncertainty (pcm)
Without BA	24318	-	33.85	11
CSBA-loaded	1155	545	30.10	12

MS rodded and EOL-unrodded pin power profile (1-Ball Design)

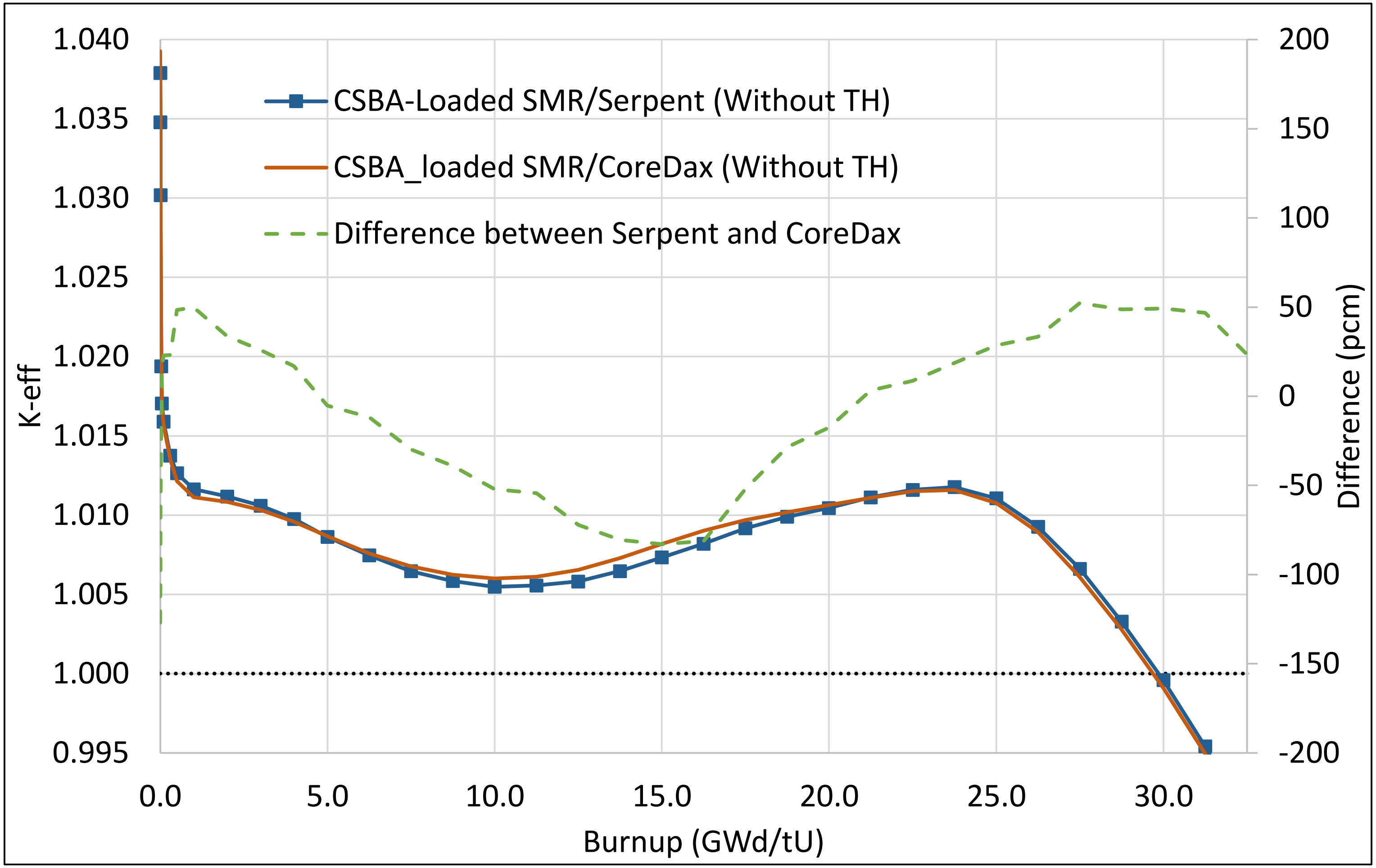
	9	10	11	12	13	14	15	16	17
1									1.038 1.022 1.021
2								0.999 0.987 0.992	1.021 1.006 1.008
3							0.991 0.991 0.987	0.996 0.987 0.983	1.015 0.999 0.998
4			0 GWd/tU 15 GWd/tU 30 GWd/tU			Rodded MS	0.995 1.000 0.999	0.995 0.987 0.989	1.009 1.001 1.000
5					0.987 0.996 0.997	0.995 1.003 1.006	0.998 1.001 1.003	0.998 0.993 0.991	1.006 1.003 0.994
6				Rodded MS	0.988 1.002 1.002	0.992 1.003 1.001	Rodded MS	0.999 1.003 1.001	1.011 1.003 1.002
7			0.994 0.997 0.999	0.994 1.001 1.001	0.982 0.988 0.988	0.984 0.989 0.988	0.991 1.000 0.999	0.991 0.991 0.990	1.008 1.001 1.000
8		1.038 1.033 1.036	1.003 1.008 1.005	0.995 1.005 1.002	0.985 0.988 0.991	0.983 0.987 0.990	0.992 0.998 0.999	0.995 0.993 0.992	1.008 1.002 1.001
9	Water Hole	1.083 1.084 1.080	1.015 1.022 1.022	Rodded MS	0.995 0.996 1.000	0.991 0.997 0.997	Rodded MS	0.998 0.998 1.002	1.010 1.004 1.001

MS rodded

	9	10	11	12	13	14	15	16	17
1									0.932
2								0.913	0.922
3							0.965	0.925	0.926
4			30 GWd/tU			unrodded MS	1.029	0.951	0.939
5					1.049	1.081	1.061	0.979	0.948
6				unrodded MS	1.066	1.062	unrodded MS	1.021	0.961
7			1.011	1.051	1.012	1.011	1.041	0.983	0.962
8		1.011	1.009	1.052	1.009	1.003	1.040	0.984	0.957
9	Water Hole	1.049	1.049	unrodded MS	1.048	1.045	unrodded MS	1.017	0.966

Unrodded MS

Comparison between Serpent and CoreDax (Without TH)

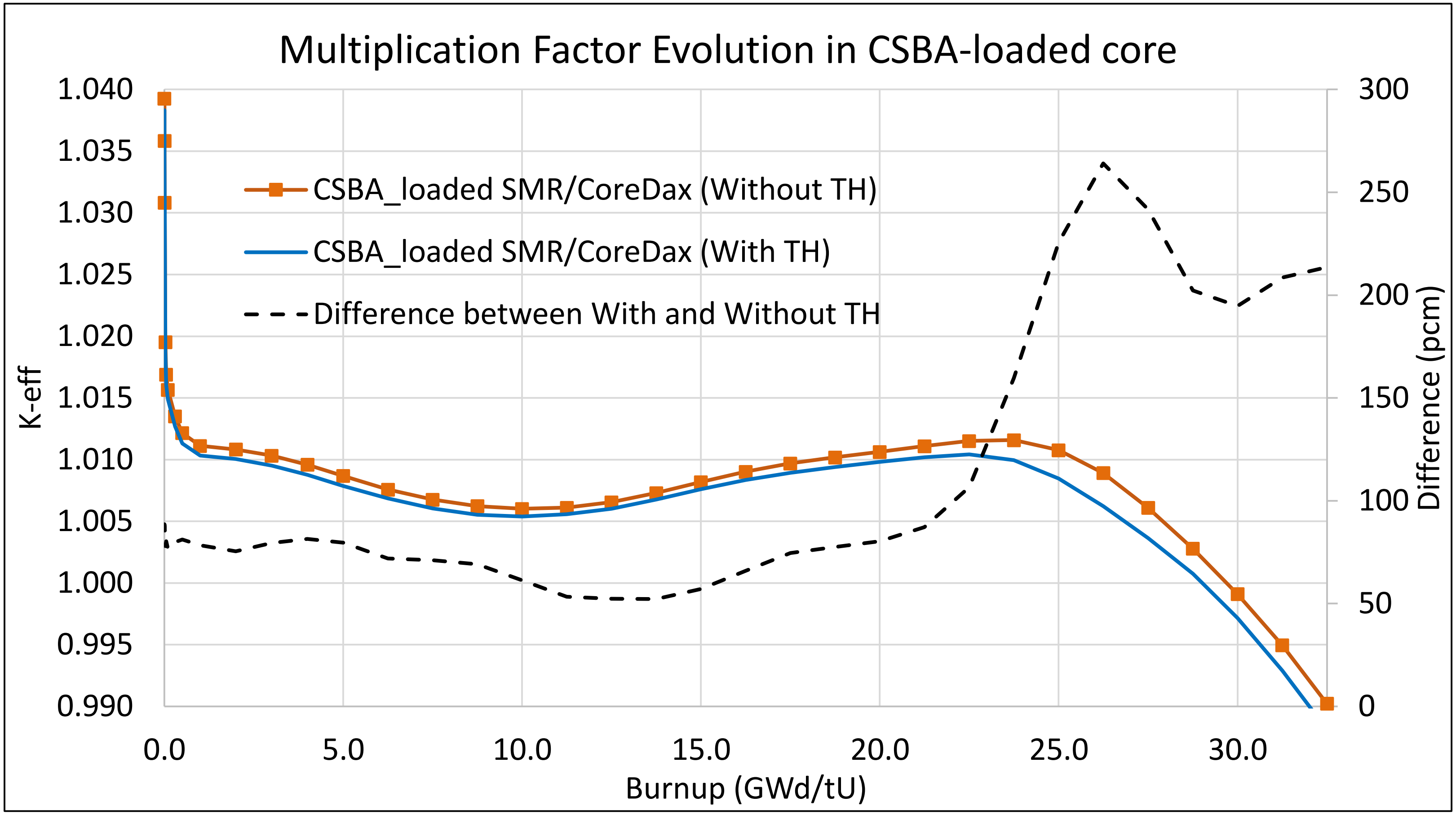


K-eff uncertainty: 12 pcm

Thermal Hydraulics Parameters

Parameter	Big-T SMR Values*
Heat source B/T fuel & coolant	97.4 / 2.4
Gap heat transfer coefficient	11345.0 (W/m^2K)
Fuel and cladding density	10.4668 / 6.522 (g/cc)
Inlet temperature	285^0C
Pressure	155 bar
Net mass flow rate	32.74 (kg/s/assembly)
# of radial mesh for fuel & clad	10 / 4

Thermal Hydraulics (TH) Coupled Neutronics Analysis



Radial Power Distribution

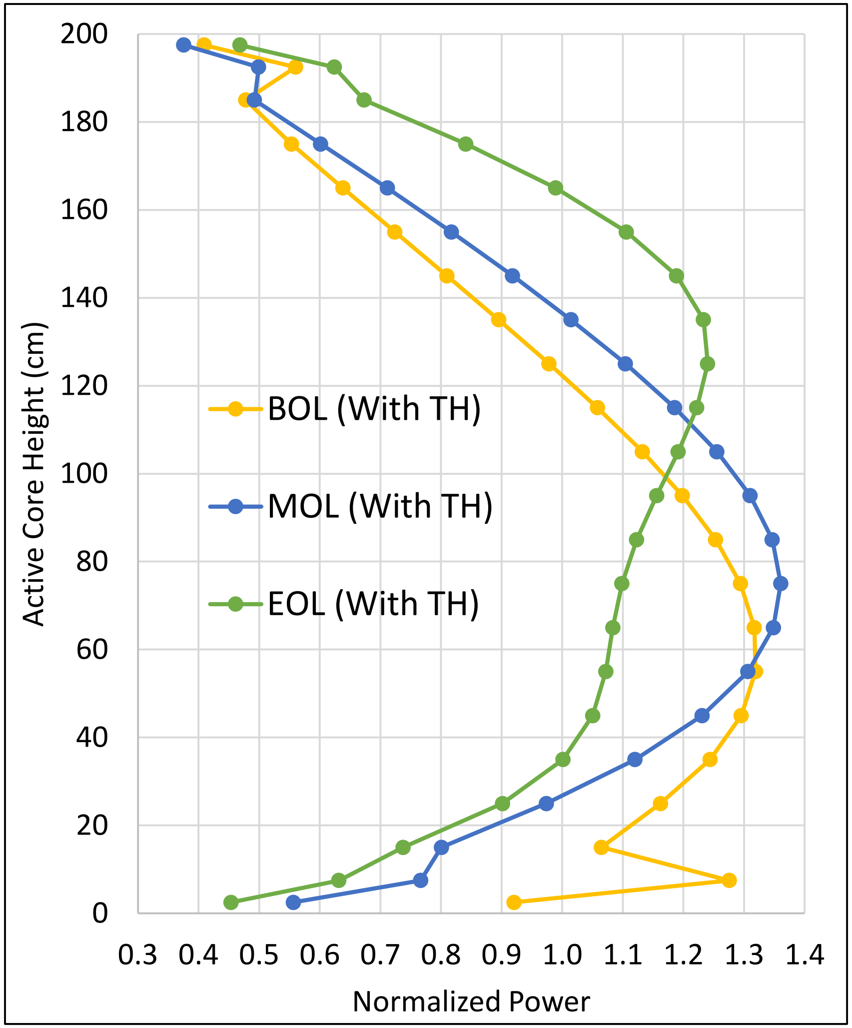
BOC MOC EOC			0.978 0.941 0.747	
		1.012 1.076 1.139	1.005 1.045 0.983	0.939 0.881 0.676
	1.019 0.99 1.239	1.018 1.027 1.183	1.032 1.084 1.081	1.074 1.018 0.798
1.021 0.964 1.277	1.02 0.976 1.258	1.017 1.013 1.201	0.999 1.059 1.107	0.815 1.059 0.799

a) Without TH

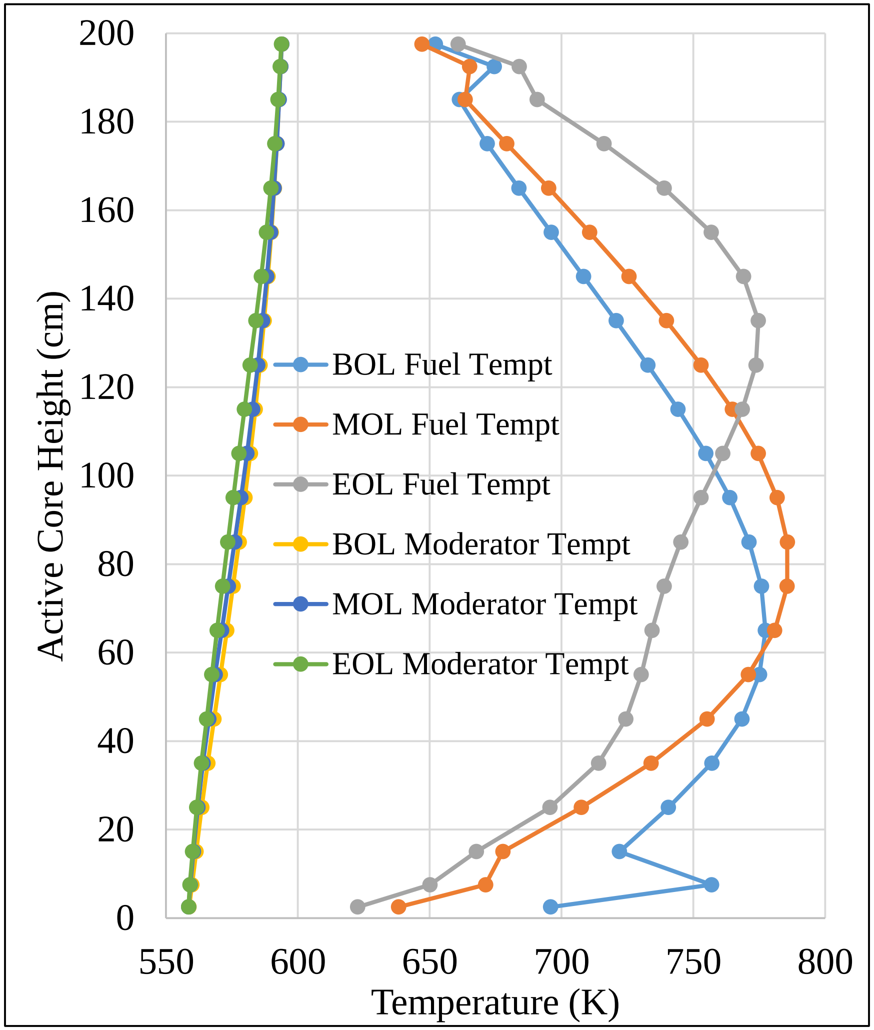
BOC MOC EOC			0.979 0.944 0.776	
		1.013 1.071 1.128	1.005 1.043 0.997	0.940 0.887 0.709
	1.02 0.992 1.193	1.018 1.025 1.156	1.03 1.079 1.082	1.067 1.016 0.829
1.022 0.97 1.218	1.021 0.98 1.205	1.017 1.012 1.168	1.000 1.056 1.102	0.823 1.056 0.826

b) With TH

Axial Power and Temperature Distributions with TH



Axial Power Distribution



Axial Temperature Distribution

Cold-Zero-Power Rod Worth Evaluation at BOL

Case	Coredax		Serpent 2		
	K-eff	Total Worth (pcm)	K-eff	Total Worth (pcm)	Rho Difference (pcm)
All rod out	1.10796	NA	1.10701	NA	77
All Rod in (Except F9)	0.97718	-12079	0.97942	-11768	-234
All Rod in (Except G9)	0.97890	-11899	0.98063	-11643	-180
All Rod in (Except E9)	0.97607	-12196	0.97900	-11812	-307
All Rod in (Except E6)	0.98679	-11083	0.98997	-10680	-326
All Rod in (Except E5)	0.97765	-12030	0.97986	-11722	-231
All rods in	0.97526	-12281	0.97838	-11876	-328

Power defect = rho (HFP) –rho (HZP) = 1306 pcm

Conclusions and Future Works

- **SBF SMR core has been successfully developed with innovative CSBA design:**
  - Minimal reactivity swing < 1200 pcm and > 400 pcm
  - Very low power peaking factors
  - Surviving through power drop transients
  - Criticality can be achievable with the use of only mechanical shim
  - Shutdown margin is assured at cold zero power condition
- **A good agreement between Serpent and Serpent-COREDAX solutions**

  → The two-step Monte Carlo-diffusion procedure can be reliably used for an SBF SMR design and analysis

Thank you for your listening
Q&A

Rod Worth Evaluation

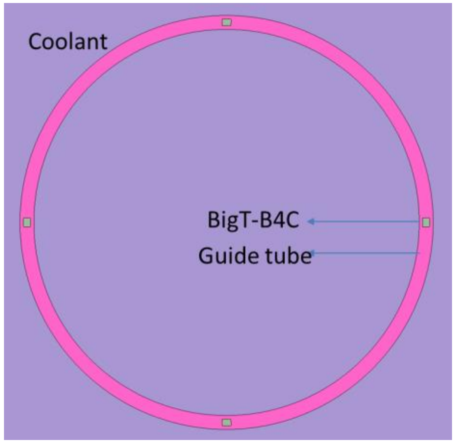
BOL condition (Hot full power)		
Case	K-eff	Total Worth (pcm)
ARO	1.03776	NA
All Mechanical Shim in (2.5% hafnium)	1.02577	-1126
All Regulating rods in (Without MS)	0.99938	-3700
All Rod in (Except F9)	0.89798	-14999
All Rod in (Except G9)	0.89855	-14929
All Rod in (Except E9)	0.89758	-15049
All Rod in (Except E6)	0.90924	-13621
All Rod in (Except E5)	0.89944	-14819
All rods in	0.89634	-15204

Power defect = rho (HFP) –rho (HZP) = 1306 pcm

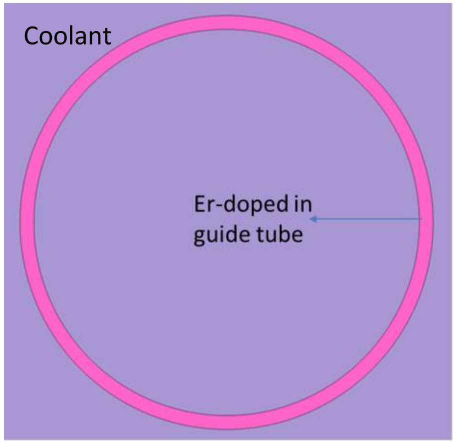
Additional Reactivity Control in CSBA-loaded Core

- **To reduce early BOC excess reactivity, several additional BA design is proposed**

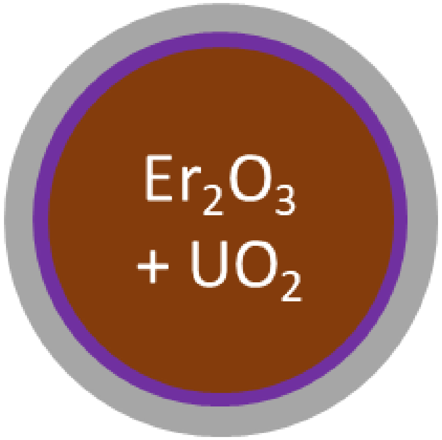
  1. BigT-B4C (**B**urnable absorber **I**ntegrated in **G**uide **T**himble-B4C)
  2. Erbium doped in guide thimble
  3. Erbium oxide (Er_2O_3) admixed in UO_2 fuel



BigT-B4C design

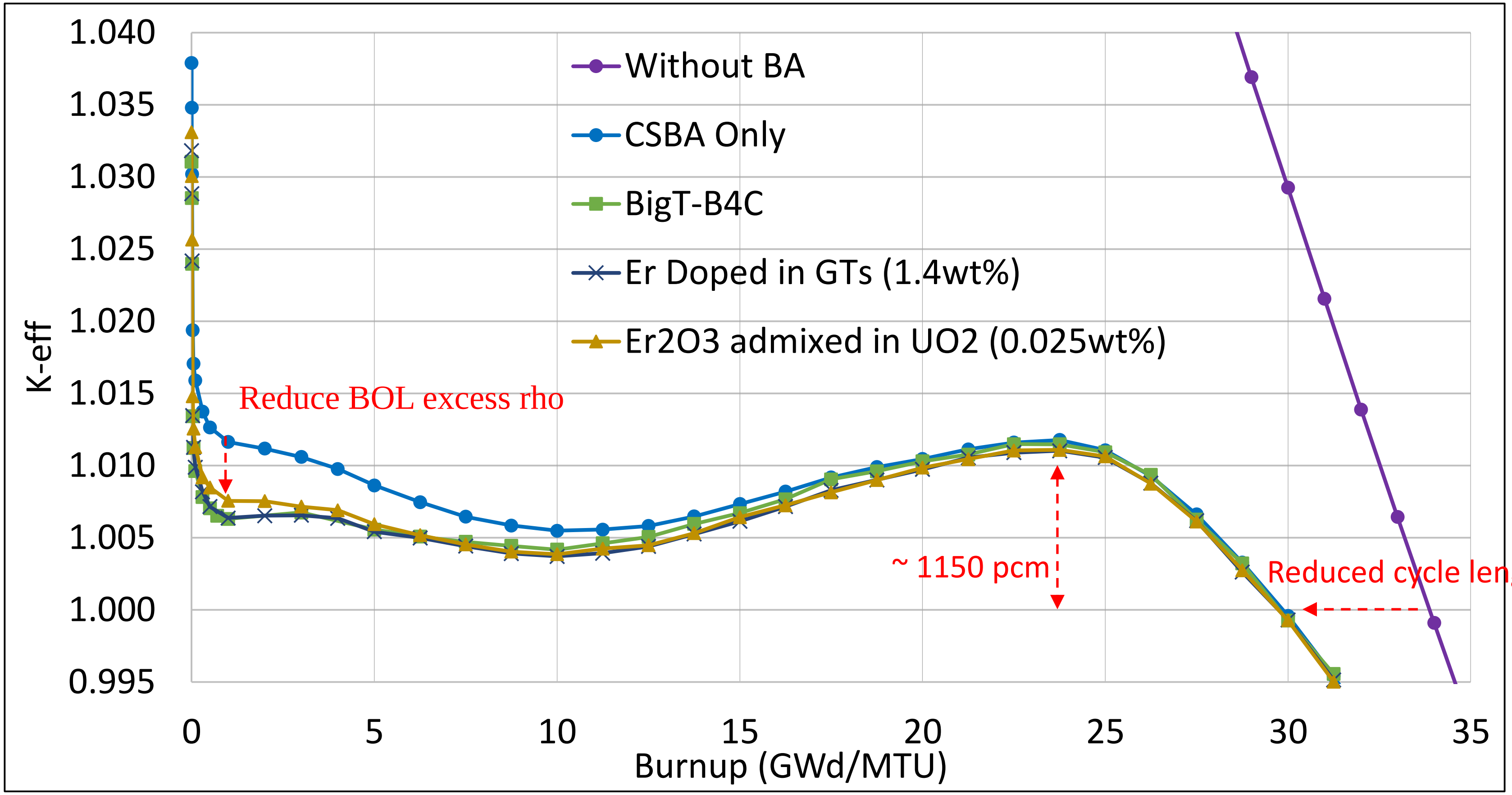


Er-doped guide thimble



Er_2O_3-UO_2 fuel pellet

Whole-core Neutronic Performance

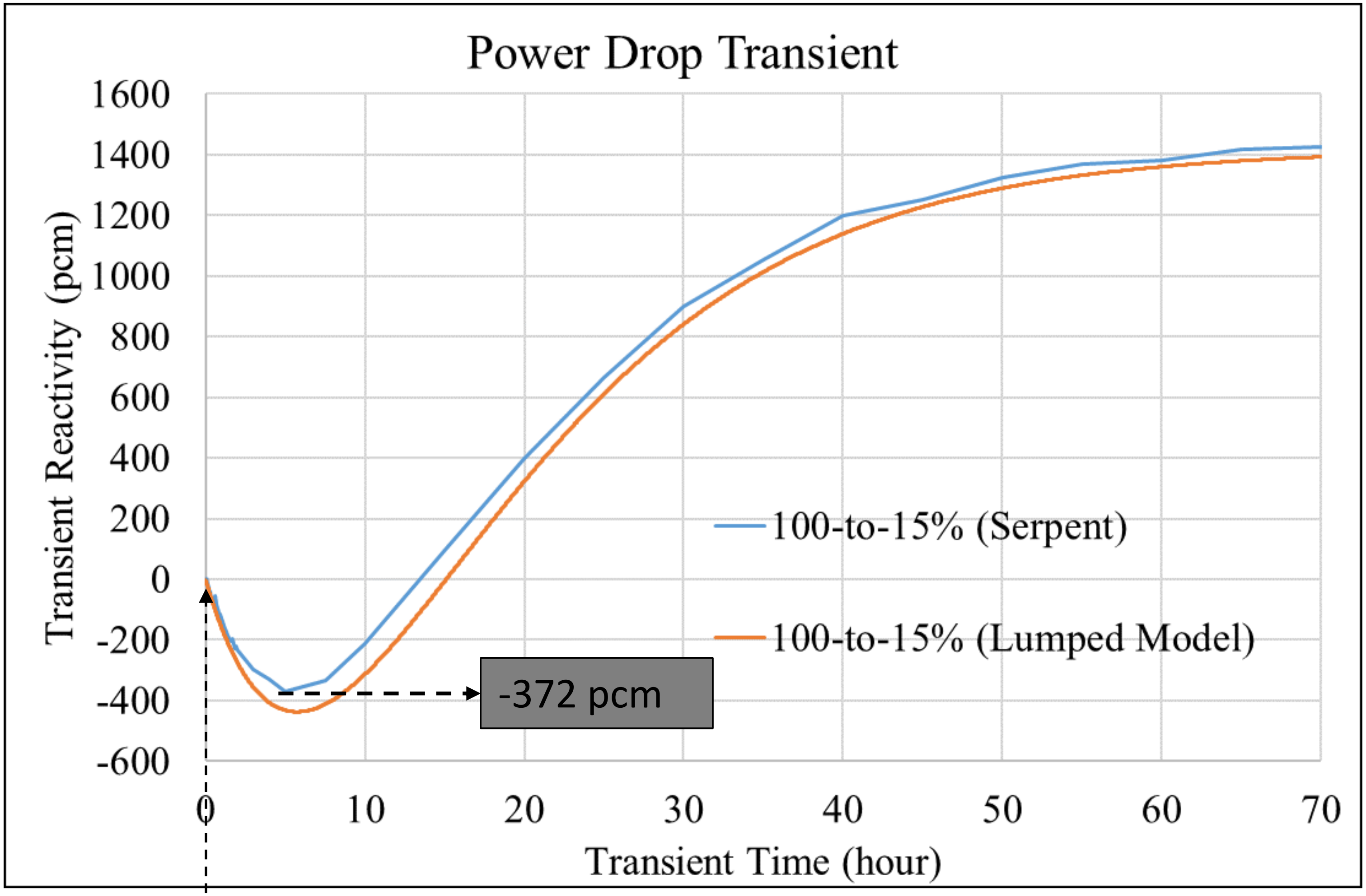


- Monte Carlo Serpent 2 code with ENDF-BVII.1 library
- 500,000 histories per cycle, 100 inactive cycles and 500 active cycles → 10 pcm uncertainty of k-eff

Burnup-dependent Fuel & Coolant Temperature Coefficients

Condition	FTC (pcm/K)	FTC STDV (pcm)	CTC (pcm/K)	CTC STDV (pcm)
BOC	-2.365	0.145	-48.114	1.47
MOC	-2.650	0.141	-51.429	1.46
EOC	-3.038	0.113	-62.853	1.37

Transient Reactivity Change after 100% to 15% Power Drop



A sudden power drop

Not consider Fuel and Coolant Tempt Coefficients