A Study on Effective Temperature of CSBA-loaded UO2 Fuel Pellet

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Outline:

1. Introduction
2. Objective
3. CSBA Design
4. Methodology
5. Numerical Results
6. Conclusion

Introduction

- Inherent safety and reliability are highly required for next-generation reactors.
- Reduction of dependence on active control systems can increase the autonomous operation.
- Soluble boron for reactivity control during the cycle is improper to meet the inherent safety.
- Soluble-Boron- Free reactor design might be feasible with innovative Burnable Absorber design concept.

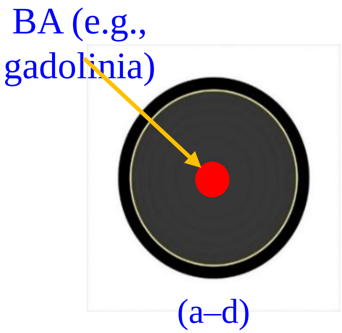
Introduction: Innovative CSBA Design

Centrally-shielded Burnable Absorber (CSBA)

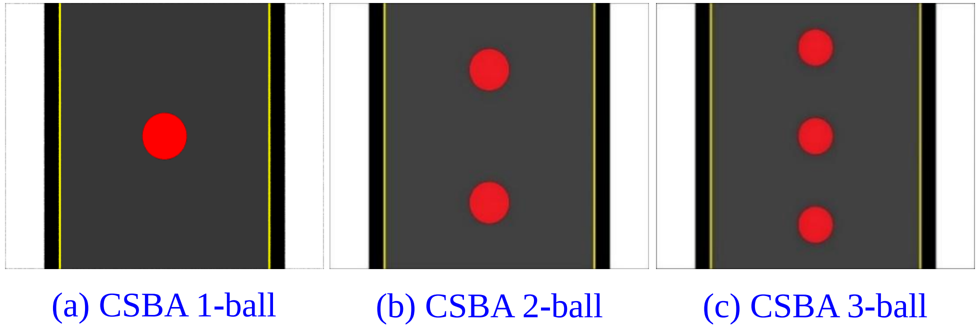
- Design concept:

  CSBA fuel rod is a typical **PWR UO_2 pellet with lumped spherical gadolinia balls inside the fuel pellet**.

- Design variants:



Top view

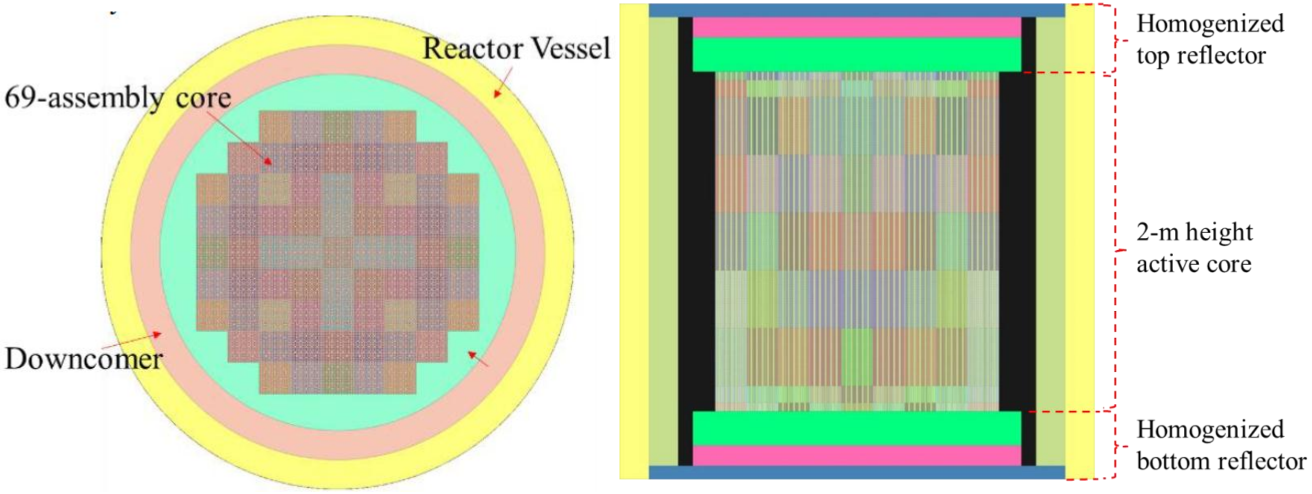


Side view

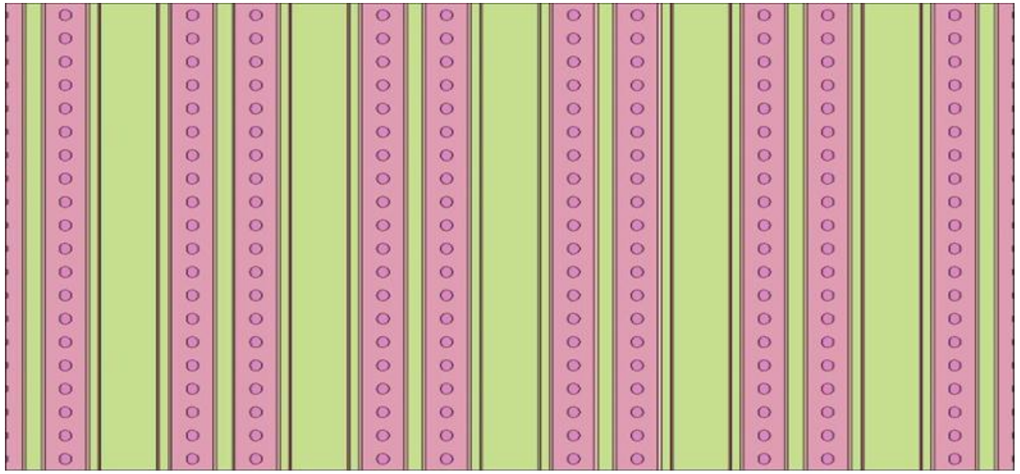
Requirement Study?

Temperature profile of the CSBA loaded fuel will be **different** compare to **typical PWR fuel pellet**. Detail Temperature profile is required for further study related with temperature.

ATOM[1] Core Configuration



Serpent model of the ATOM core



CSBA loading in the ATOM fuel pellets

Parameters	**Target Value**	**Unit**
Thermal power	450	MWt
Active core height	200	cm
Equivalent diameter	201.6	cm
Height-to-diameter ratio	0.993	
Power density	**25.99**	**W/gU**
Cycle length	> 48	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	pcm
Boron concentration	0	ppm

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

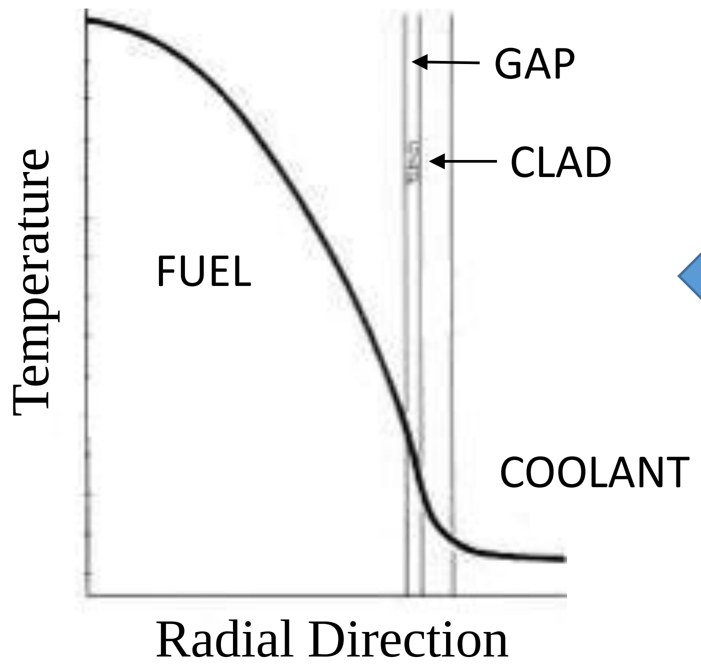
[1]**ATOM**: Autonomous Transportable On-demand Reactor Module

Ref.: Xuan Ha Nguyen, Ahmed A. E. Abdelhameed and Yonghee Kim, **Optimization of Centrally Shielded Burnable Absorbers in Soluble-Boron-Free SMR Design,** *Transactions of the Korean Nuclear Society Autumn Meeting Gyeongju, Korea, October 25-27, 2017.*

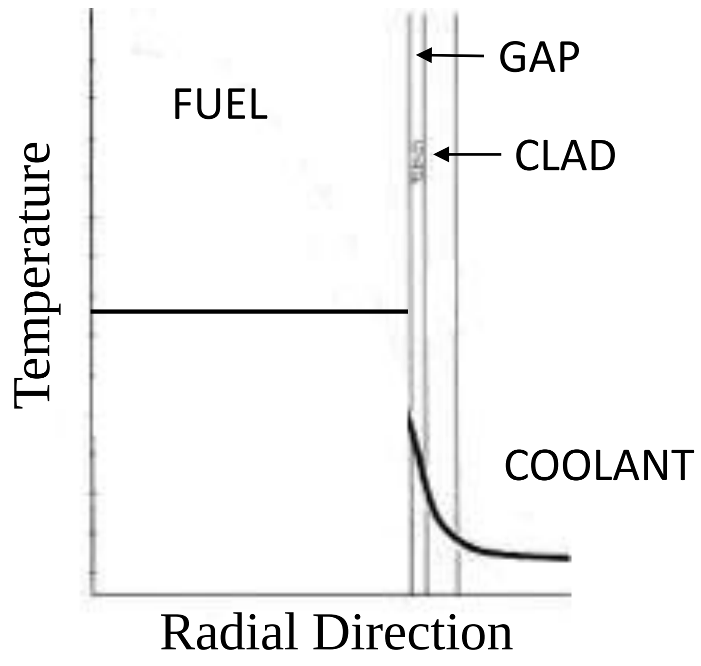
Objective

Objective:

- To find a effective temperature of the fuel for neutronics calculation.
- To find detail temperature profile of a fuel pellet.



Temperature Distribution of a Standard Fuel



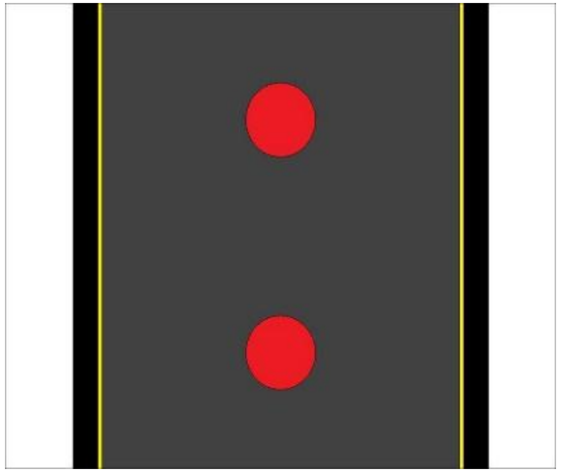
Target

CSBA Pellet Design

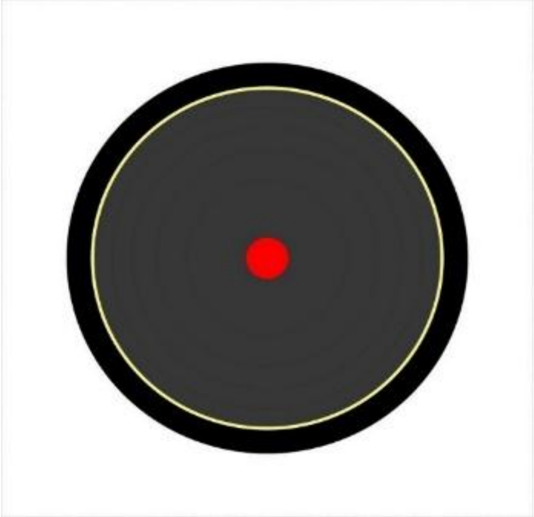
Fuel pellet design parameters

Parameters	Value
Power density (W/gU)	25.99
UO2 density (g/cm3)	10.4668
UO_2 pellet height (cm)	1.00
UO_2 pellet radius (cm)	0.40958
Clad inner radius (cm)	0.41873
Clad outer radius (cm)	0.47600
CSBA ball radius (cm)	0.1
Number of CSBA ball	2

Coolant Temperature: 575 K



side view



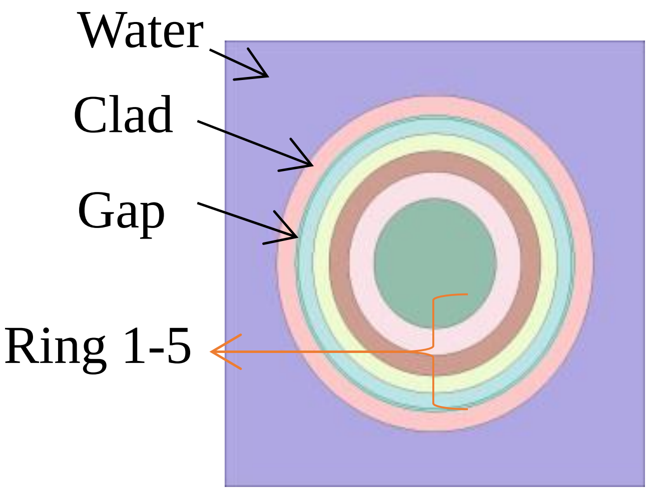
Top view

Methodology

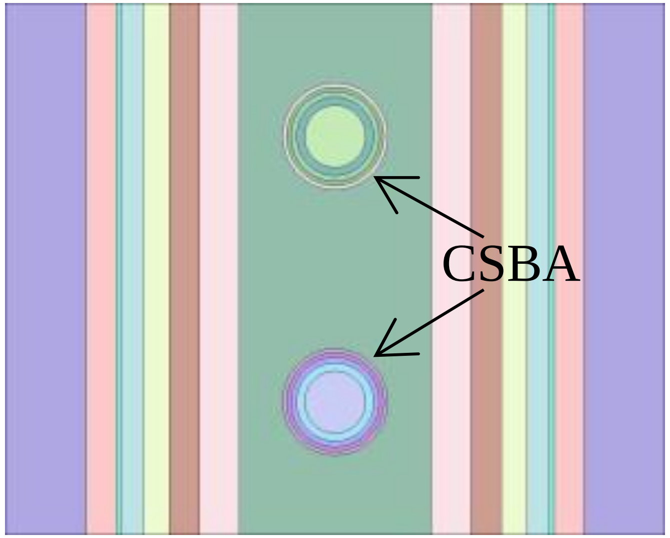
1. Active fuel pellet divided by 5 (five) equal volumes.
2. Power distribution of the fuel pellet was updated from **Monte Carlo Serpent Code**.
3. Temperature distribution was updated by solving the **steady state heat conduction equation**.
   - Steady state heat conduction equation solved by using Finite Element Method (FEM).

     The volume average temperature $\bar{T}$ is

$$\bar{T} = \frac{\int T(r).dV}{\int dV}$$



Top view



Side view

Heat Conduction Equation

Steady state heat equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k_r . r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k_\varphi . r\frac{\partial T}{\partial \varphi}\right)+\frac{\partial}{\partial z}\left(k_z . \frac{\partial T}{\partial z}\right)+\dot{g}=0$$

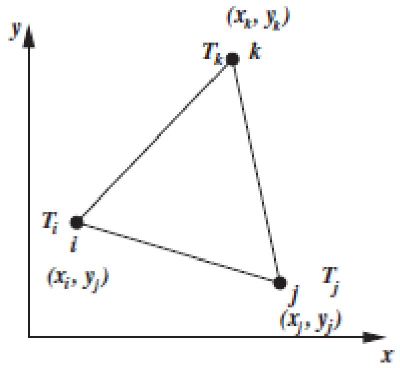
Due to axisymmetric

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k_r . r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k_z . \frac{\partial T}{\partial z}\right)+\dot{g}=0$$

Heat conduction equation solved using the **Galerkin method** for Triangular Element.

Heat equation as integral form: $\int_{\Omega} N_i[\frac{k_r}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+k_z\frac{\partial^2 T}{\partial z^2}+G]=0$

Triangular Element



Solution of above equation as matrix form $[K]\{T\}=\{f\}$

$\{T\}$ = Temperature matrix

$$[K]=\int_{\Omega}[B]^T[D][B]d\Omega+\int_{\Gamma}h[N]^T[N]d\Gamma$$

$$\{f\}_e=\int_{\Omega}G[N]^T r_e d\Omega-\int_{\Gamma_q}q[N]^T r_e d\Gamma+\int_{\Gamma_h}hT_a[N]^T r_e d\Gamma$$

Thermal Conductivity

Thermal Conductivity of UO_2 (W/m·K)

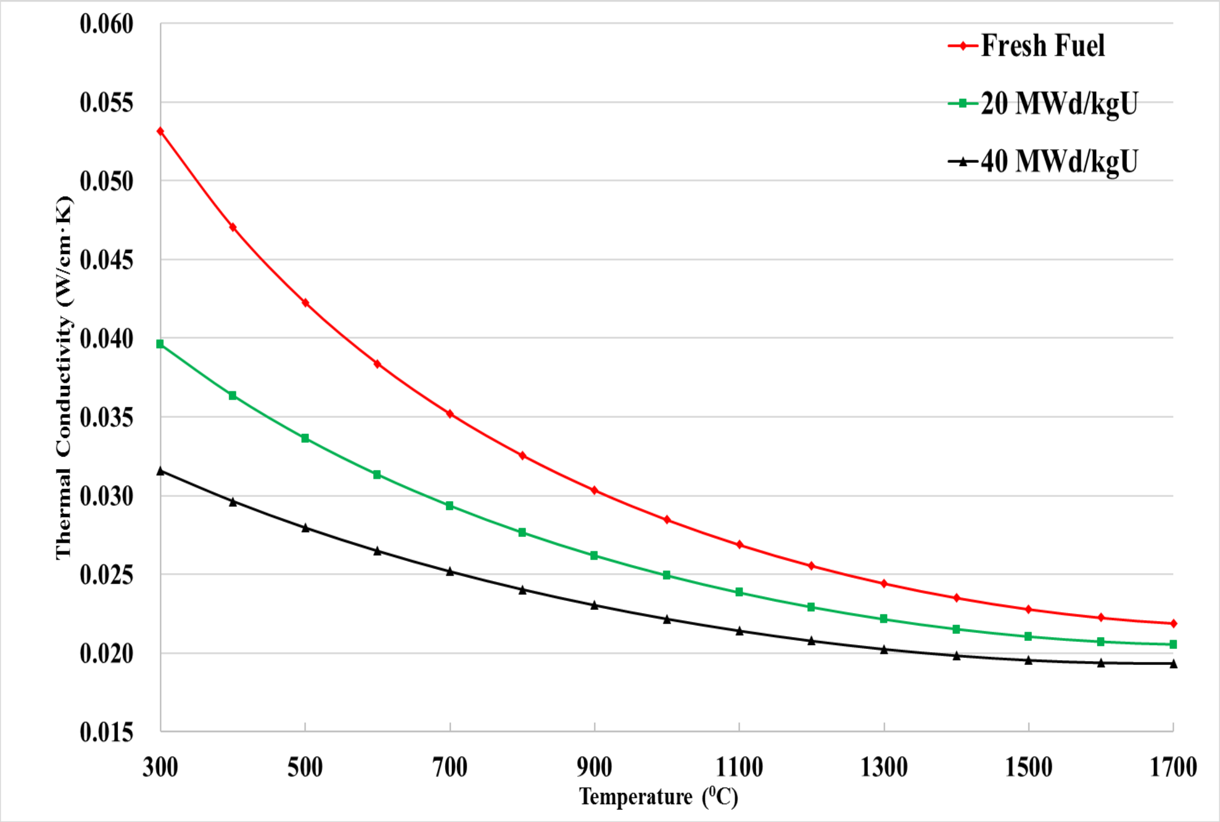
$$k = \frac{1}{0.1148+0.0035B+2.475\text{x}10^{-4}(1-0.00333B)T} + 0.0132\ \exp(0.00188T)$$

where T in ^{0}C, B in MWd/kgU

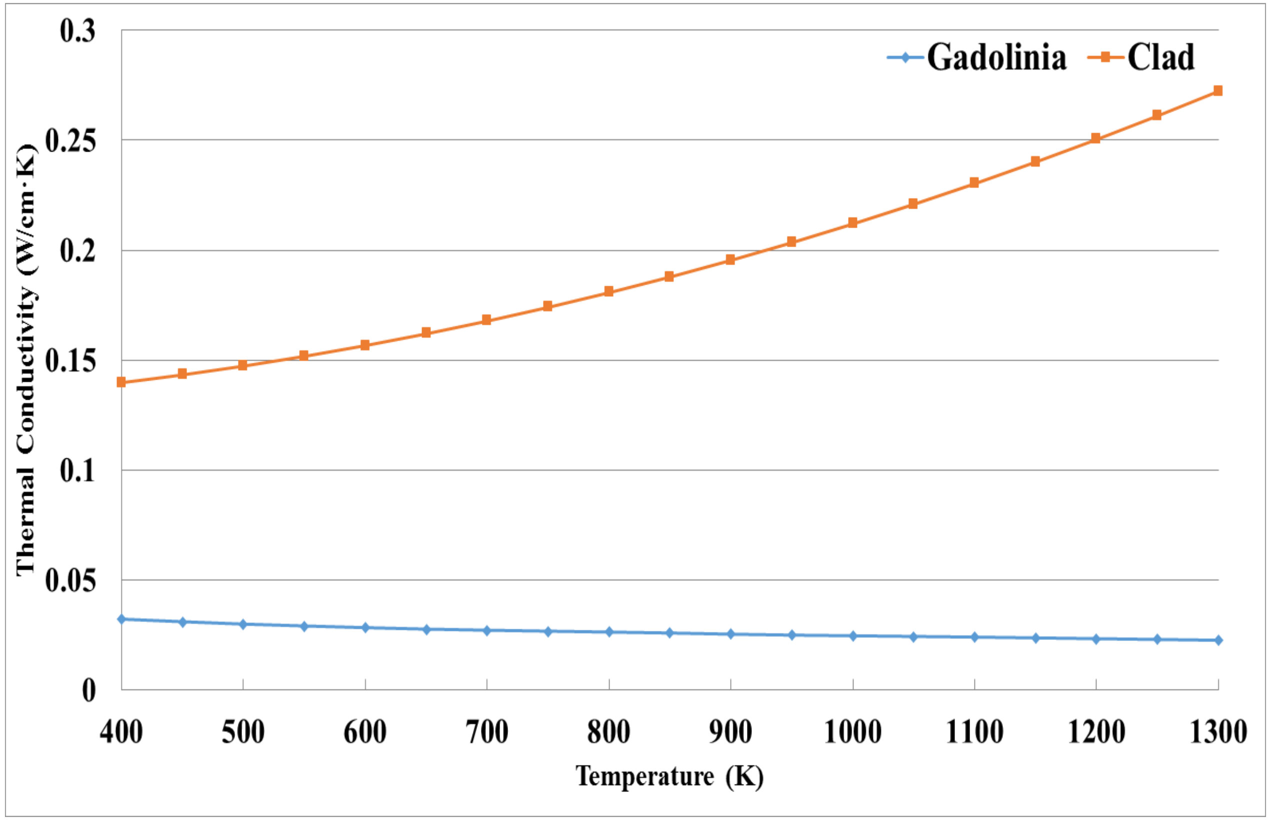
Thermal Conductivity of Clad (W/m·K)

$$k = 12.767 - 5.4348\text{x}10^{-4}T + 8.9818\text{x}10^{-6}T^2$$

where T in K



Burnup-dependent thermal conductivity of UO_2

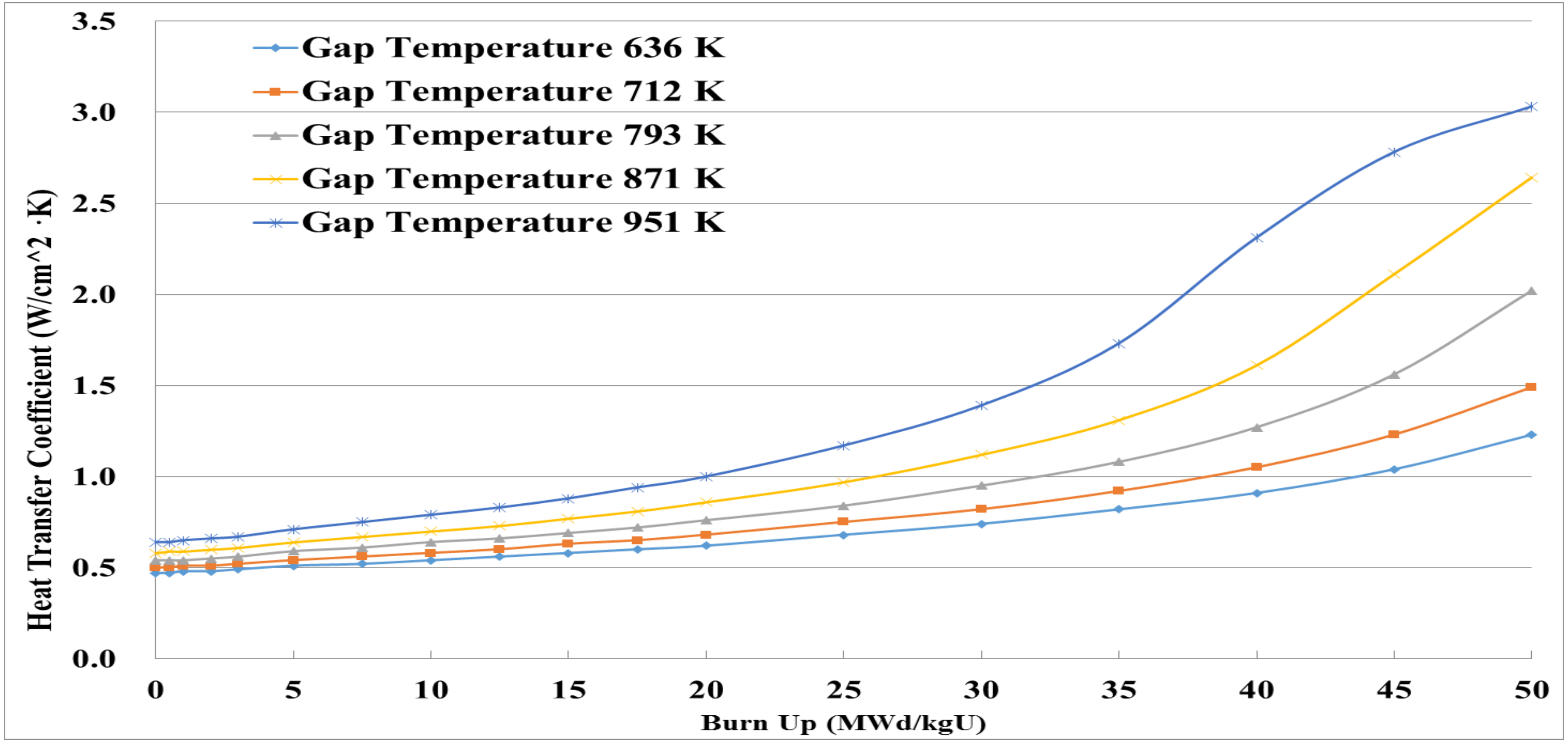


Thermal conductivity of Clad and Gadolinia

Heat Transfer Coefficients

Heat transfer coefficient clad to coolant: **0.9 W/cm²·K**

Heat transfer coefficient between gap:



Burnup-dependent heat transfer coefficient between fuel gap

Error Analysis (Temperature)

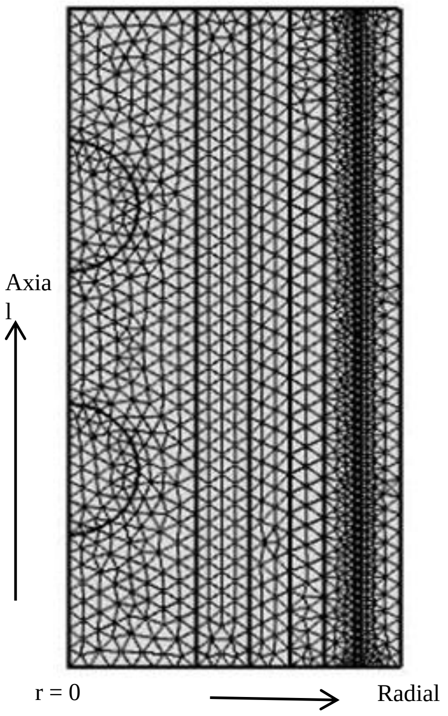
Reference Solution: COMSOL Multiphysics

Mesh Information: Reference

Parameters	Values
Number of mesh points	5809
Number of mesh Elements	11333
Maximum element size (cm)	0.01
Minimum element size (cm)	2E-5

Mesh Information: Solved FEM

Parameters	Values
Number of mesh points	1252
Number of mesh Elements	2387
Maximum element size (cm)	0.03
Minimum element size (cm)	2E-4



Power density: 400 W/cm^3, h_gap: 0.52 W/cm^2·K and Clad conductivity 0.17 W/cm·K

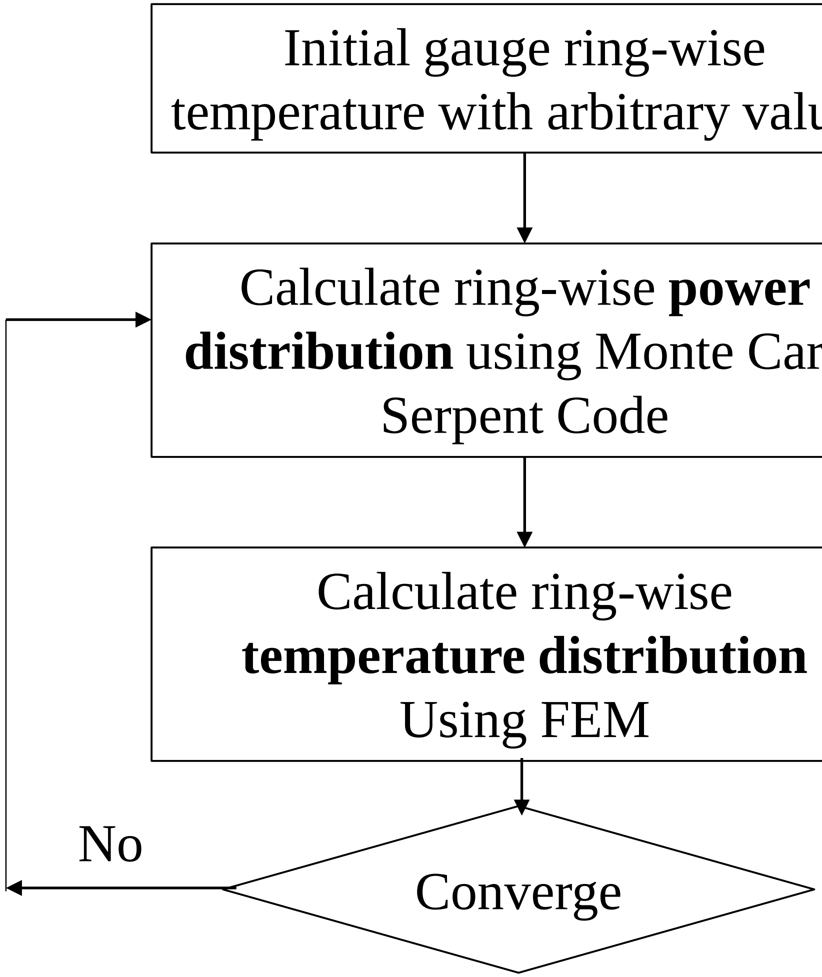
- **Case 1**: Thermal conductivity UO_2 **0.02 W/cm·K**, Gadolinia (Gd_2O_3) **0.020 W/cm·K**
- **Case 2**: Thermal conductivity UO_2 **0.06 W/cm·K**, Gadolinia (Gd_2O_3) **0.025 W/cm·K**
- **Case 3**: Thermal conductivity UO_2 **0.02 W/cm·K**, Gadolinia (Gd_2O_3) **0.035 W/cm·K**

Case 1		**Case 2**		**Case 3**	
Max. relative Error (single point) %	RMS error	Max. relative Error (single point) %	RMS error	Max. relative Error (single point) %	RMS error
0.165	0.7325	0.0844	0.2573	0.164	0.7367

Cause of Error: Solved FEM calculate CSBA volume 1.3 % less from actual volume.

Methodology: Algorithm

1. Detail temperature distribution:



2. Effective temperature:

- Preserve the multiplication factor.
- Calculate effective temperature within 6.5 pcm uncertainty.

3. Volume-average temperature:

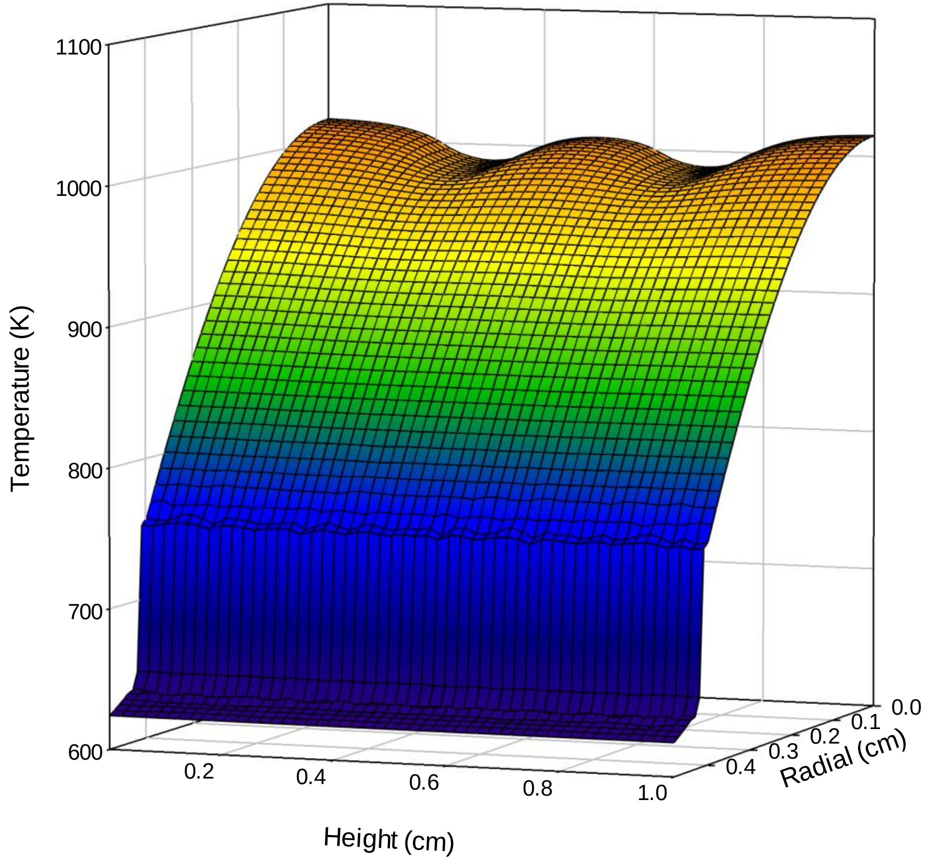
- Calculate volume average temperature

$$\bar{T} = \frac{\int T(r) \, . \, dV}{\int dV}$$

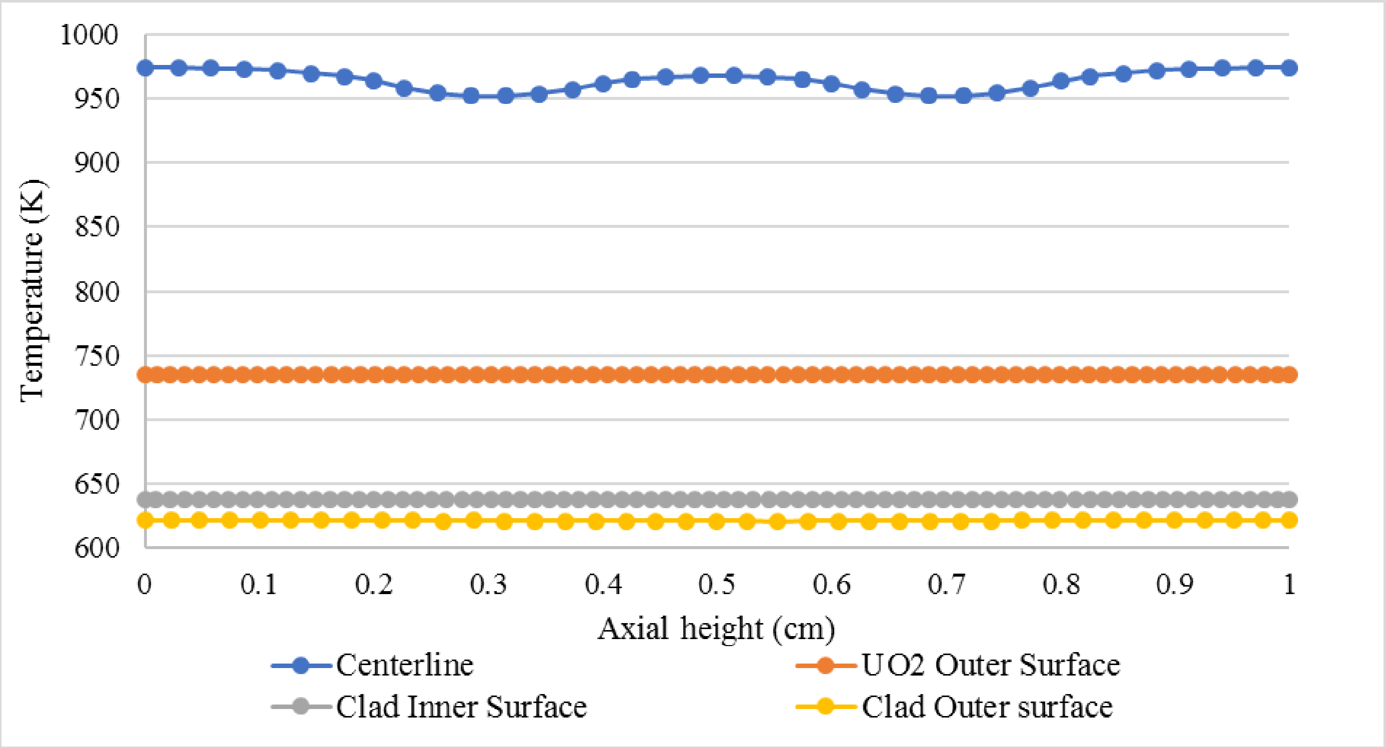
- Calculate multiplication factor using Monte Carlo Serpent Code.

Numerical Results

Temperature profile of 2 ball CSBA pellet:



Temperature distribution

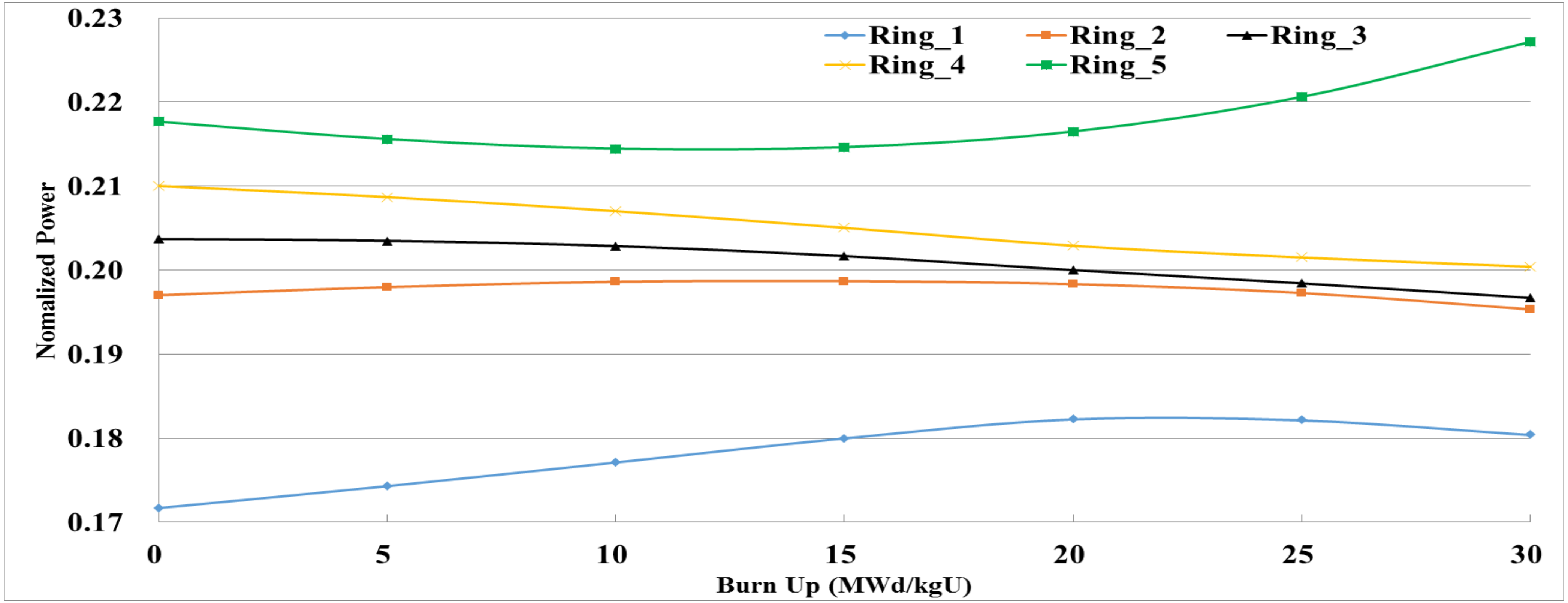


Temperature distribution

Numerical Results

Ring-wise power distribution:

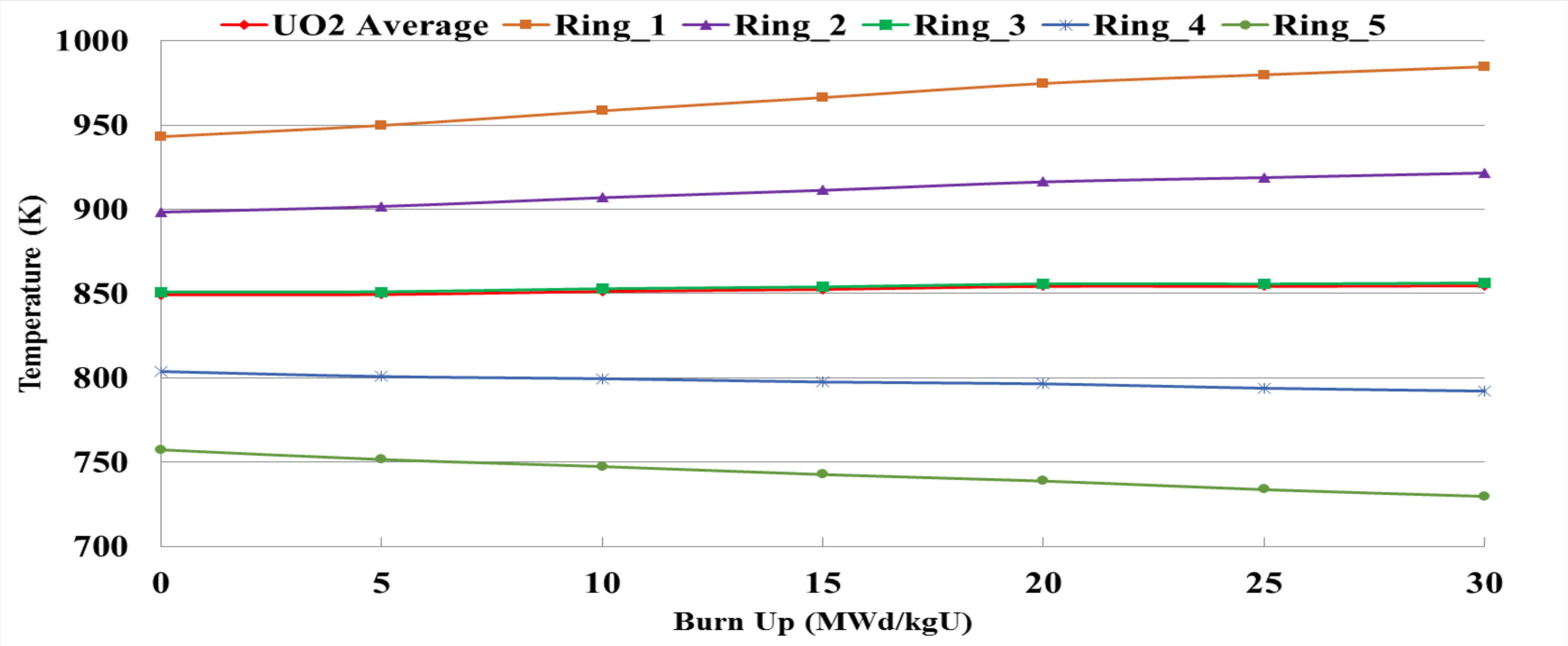
Burnup (GWd/MTU)	0.0	5.0	10.0	15.0	20.0	25.0	30.0
Ring 1	0.171680	0.174300	0.177130	0.180010	0.182280	0.182160	0.180410
Ring 2	0.197000	0.197970	0.198610	0.198690	0.198330	0.197260	0.195290
Ring 3	0.203670	0.203460	0.202830	0.201650	0.199990	0.198420	0.196690
Ring 4	0.209980	0.208670	0.206990	0.205030	0.202910	0.201530	0.200430
Ring 5	0.217670	0.215590	0.214440	0.214620	0.216490	0.220630	0.227190



Numerical Results

Volume-average temperatures:

Burnup (GWd/MTU)	0.0	5.0	10.0	15.0	20.0	25.0	30.0
Ring 1	943.32	949.95	958.56	966.35	974.65	979.75	984.45
Ring 2	898.38	901.78	906.98	911.35	916.32	918.88	921.61
Ring 3	850.81	850.97	852.83	853.92	855.72	855.70	856.27
Ring 4	803.64	800.76	799.52	797.61	796.51	793.98	792.33
Ring 5	757.47	751.72	747.56	742.83	738.98	733.91	729.89
UO2 Average	849.25	849.46	851.41	852.63	854.55	854.48	854.88



Numerical Results

Burnup-dependent multiplication factors at different temperatures

Burnup (MWd/kgU)	k_{inf} (reference)	k_{inf} (T_{eff})	Effective T (K)	Difference* (pcm)	k_{inf} (T_{avg})	Average T (K)	Difference ** (pcm)
0	1.150166	1.150173	**839.50**	-0.53	1.149783	**849.25**	28.96
10	1.016021	1.016023	**839.70**	-0.09	1.015740	**851.41**	27.23
20	0.964887	0.964875	**845.75**	1.30	0.964546	**854.55**	36.64
30	0.832647	0.832630	**839.71**	2.44	0.832231	**854.88**	60.03

* Difference between k_{inf} (T_{eff}) and k_{inf} (reference), ** Difference between k_{inf} (T_{avg}) and k_{inf} (reference)

Conclusion

- The coupled calculation with Serpent and FEM based T/H calculation is successfully performed with burnup-dependent power and temperature distribution of newly proposed CSBA fuel design.
- Steady state heat conduction solved by FEM (Galerkin method).
- Iteration calculation executed between Monte Carlo Serpent Code and FEM based T/H solution.
- Effective Temperature is calculated to preserve the reaction rate of the reactor.
- The Effective Temperature is lower than volume-average temperature, due to higher importance of periphery region

Thank You

Question ?

Numerical Results

Burnup (MWd/kgU)	CSBA Design		Standard PWR [Power Density: **25.99 W/gU**]				
	Average T (K)	Effective T (K)	Average T (K)	Centerline	Surface (UO2)	**Effective T[1] (K)**	**Effective T[2] (K)**
0	849.25	839.50	855.85	976.79	737.12	**832.99**	**854.15**
10	851.41	839.70	858.30	996.32	724.23	**833.07**	**856.67**
20	854.55	845.75	861.74	1016.79	712.68	**834.32**	**860.24**
30	854.88	839.71	862.26	1029.42	700.74	**832.21**	**859.83**

1. Alexander Kudrov1 et al. Effective fuel temperature of WWER-1000, MATEC Web of Conferences 110, 01046 (2017)

$$T_{eff} = T(r_0) + 0.4[T(0) - T(r_0)]$$

2. Goltsev A.O. et al. Computational problems in the calculation of temperature effect for heterogeneous Nuclear reactor unit cells, Annals of nuclear energy 27 (2000) 175-183

$$T_{eff} = \frac{1}{3}[T(r_0) + T(0) + \sqrt{T(r_0).T(0)}\ ]$$

Numerical Results

Burnup (MWd/kgU)	CSBA Design		Standard PWR [Power Density: **38 W/gU**]				
	Average T (K)	Effective T (K)	Average T (K)	Centerline	Surface (UO_2)	**Effective T[1] (K)**	Effective T[2] (K)
0	849.25	839.50	986.16	1200.92	805.57	**963.71**	996.69
10	851.41	839.70	989.17	1228.59	787.01	**963.64**	999.64
20	854.55	845.75	993.38	1257.36	770.31	**965.13**	1003.94
30	854.88	839.71	993.24	1273.90	753.66	**961.76**	1002.47

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