Core Design Study of Ultra-long Cycle Fast Reactor Concept

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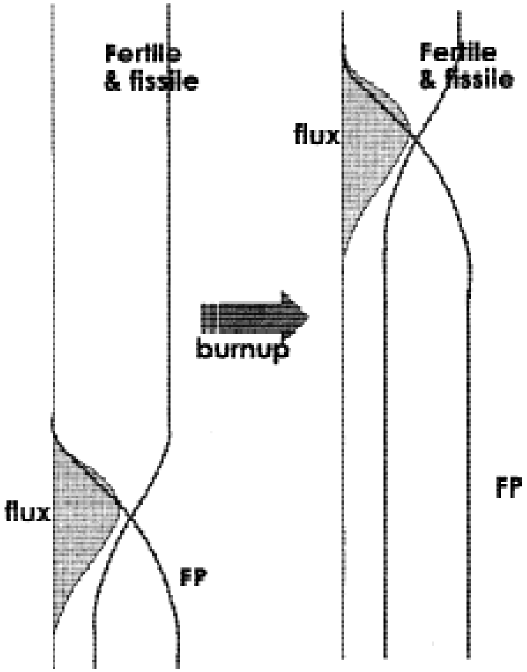
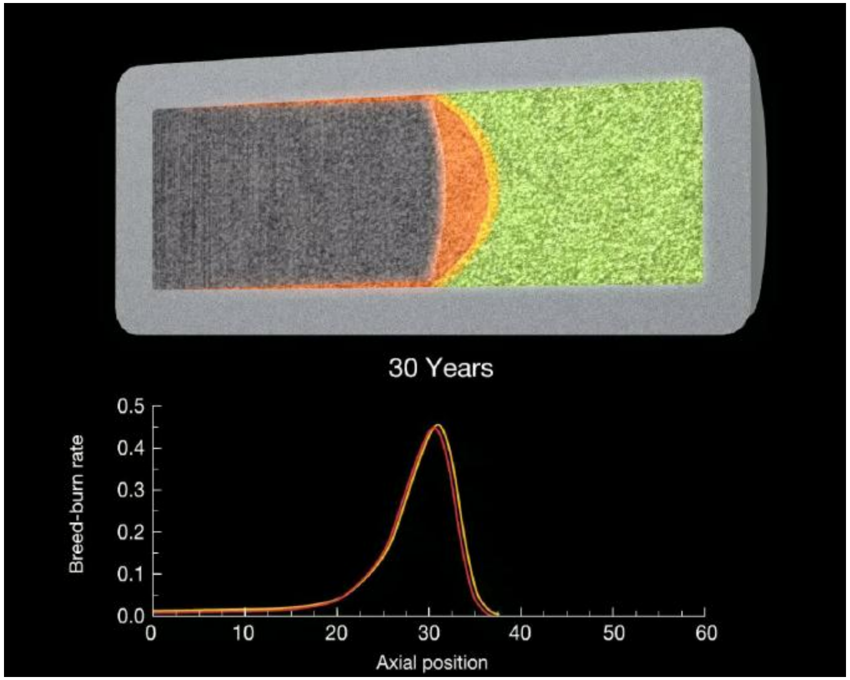
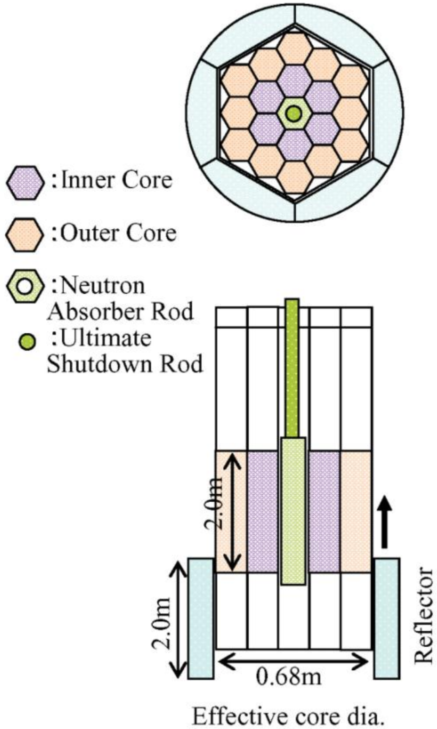
- UCFR (Ultra-long Cycle Fast Reactor)
- For uranium utilization & Nuclear non-proliferation



*CANDLE



**TWR



***4S

Figure 1. Fast reactor concepts

*CANDLE: The New Burnup Strategy", Hiroshi Sekimoto, 2001
**Nuclear initiative, Terrapower LLC, 2009
***Sodium Cooled Small Fast Long-Life Reactor "4S", Nobuyuki Ueda, 2005

I. Introduction

- CANDLE, TWR, 4S, AFR and KALIMER
- FR technologies and materials are under development
- UCFR has relatively extreme condition (fuel volume ratio, neutron flux (fluence), coolant flow, pressure drop)
- **Korea has 19 PWRs and discharge spent fuel over 300t/year**
- Design and evaluations were performed by McCARD Monte Carlo code

- UCFR-1000 & UCFR-100

- Natural Uranium & Spent Fuel

Table I. PWR spent fuel composition

Element or Iotope	wt.%	Element or Iotope	wt.%	Element or Iotope	wt.%
Ge	9.00E-05	Ba	2.47E-01	U-235	9.72E-01
Rb	1.00E-01	La	1.68E-01	U-236	5.89E-01
Sr	6.00E-02	Ce	3.22E-01	U-238	9.41E+01
Zr	5.10E-01	Pr	1.53E-01	Np-237	5.76E-02
Nb	5.50E-07	Nd	5.55E-01	Pu-238	1.94E-02
Mo	3.30E-01	Pm	1.50E-03	Pu-239	5.22E-01
Tc	1.05E-01	Sm	1.11E-01	Pu-240	2.47E-01
Ru	2.96E-01	Eu	1.71E-02	Pu-241	8.38E-02
Rh	6.00E-02	Gd	1.68E-02	Pu-242	6.27E-02
Pd	1.76E-01	Tb	3.00E-04	Pu-244	1.83E-06
Ag	9.30E-03	Dy	1.60E-04	Am-241	5.82E-02
In	3.80E-04	Ho	1.40E-05	Am-242	1.34E-02
Sn	1.10E-02	Er	3.10E-06	Am-243	1.35E-04
Sb	2.30E-03	U-234	1.95E-03	Cm-242	2.62E-07

II. Core Design of UCFR

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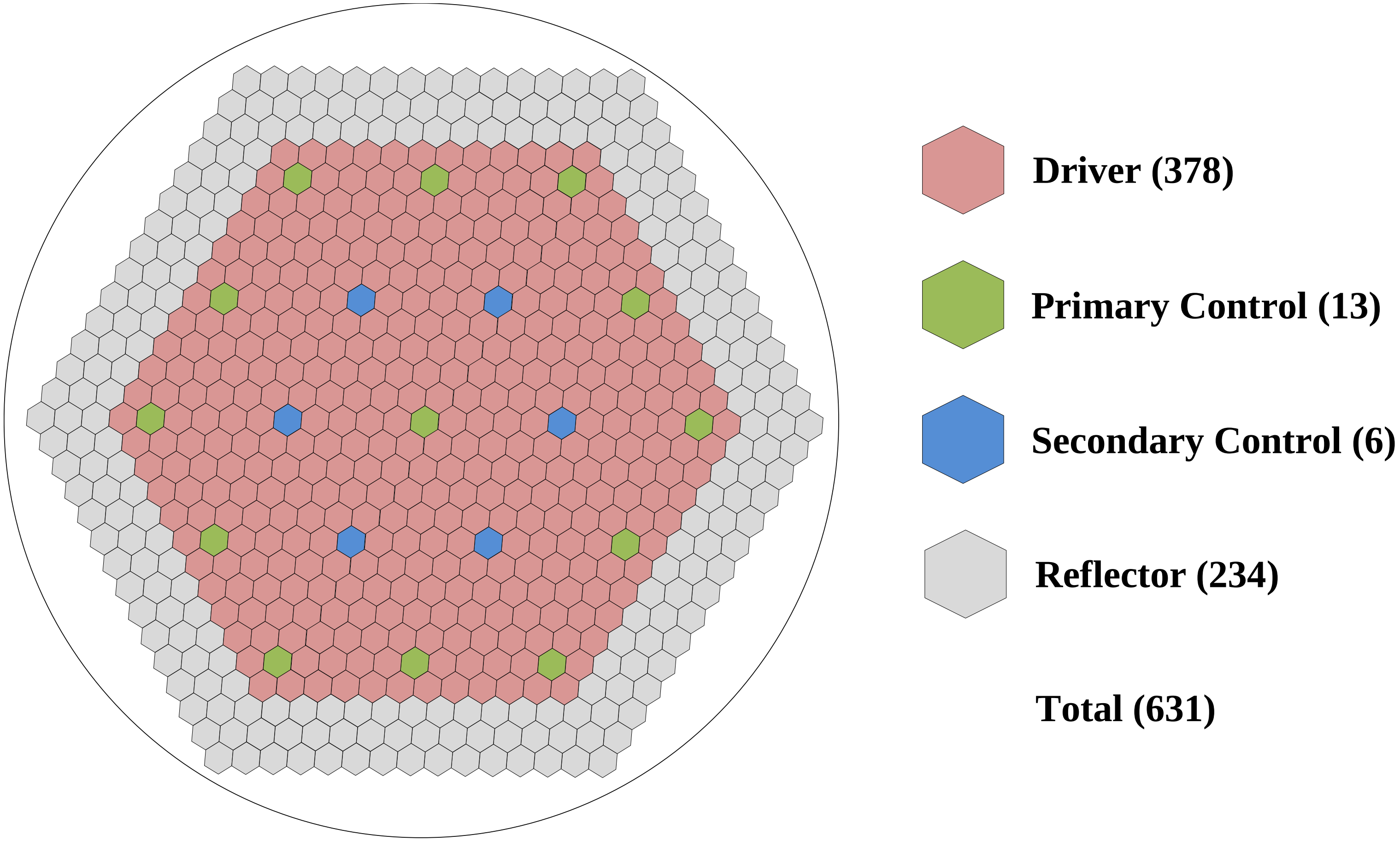


Figure 2. Core layout of UCFR-1000

- Control assembly
  1) primary (natural boron)
  2) secondary (90% enriched B-10)

II. Core Design of UCFR

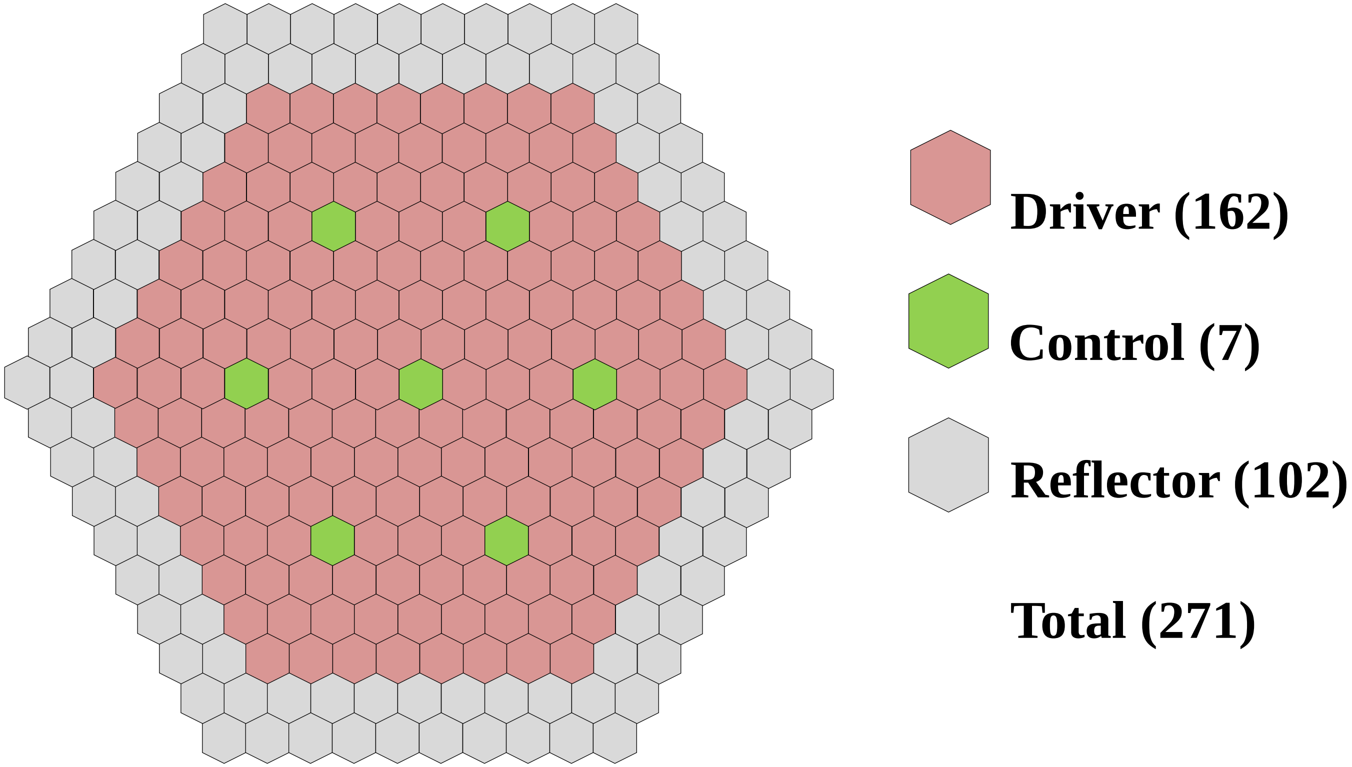


Figure 3. Core layout of UCFR-100

- Control assembly: 90% enriched B-10

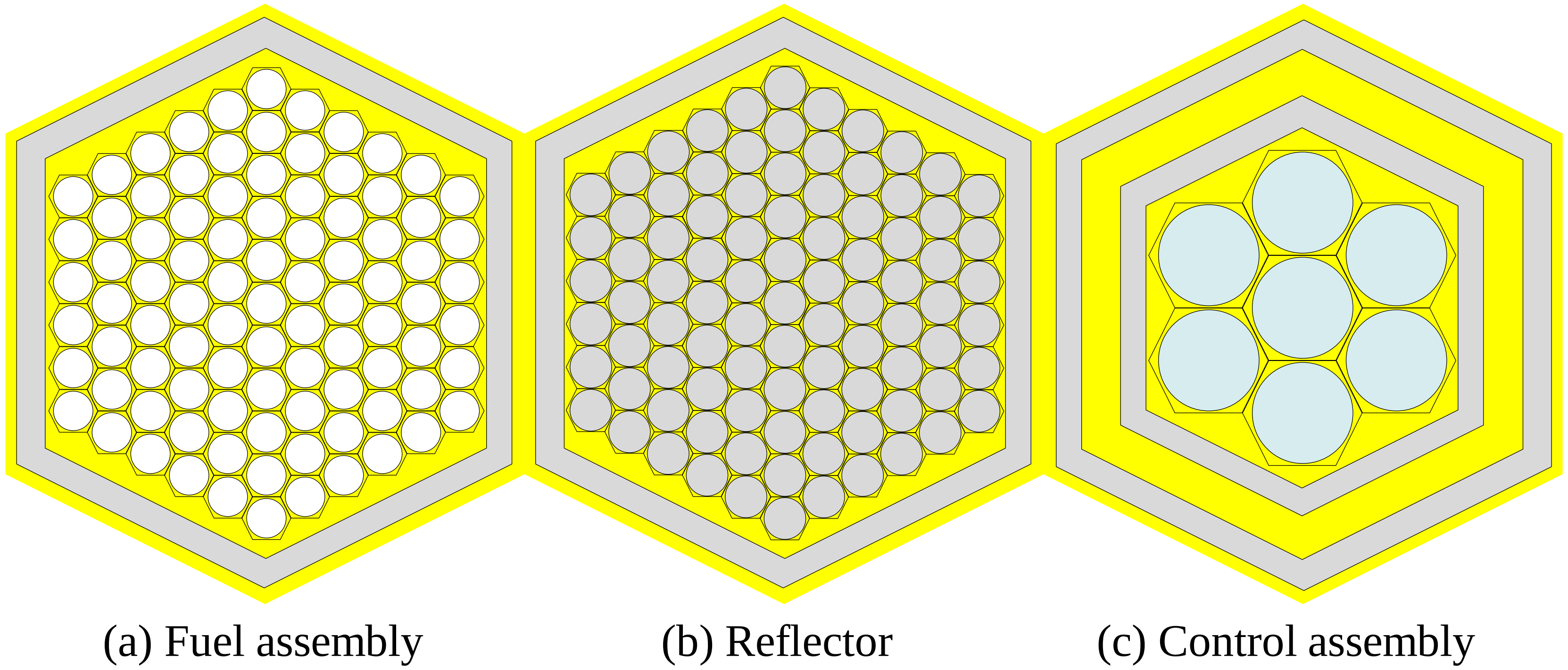
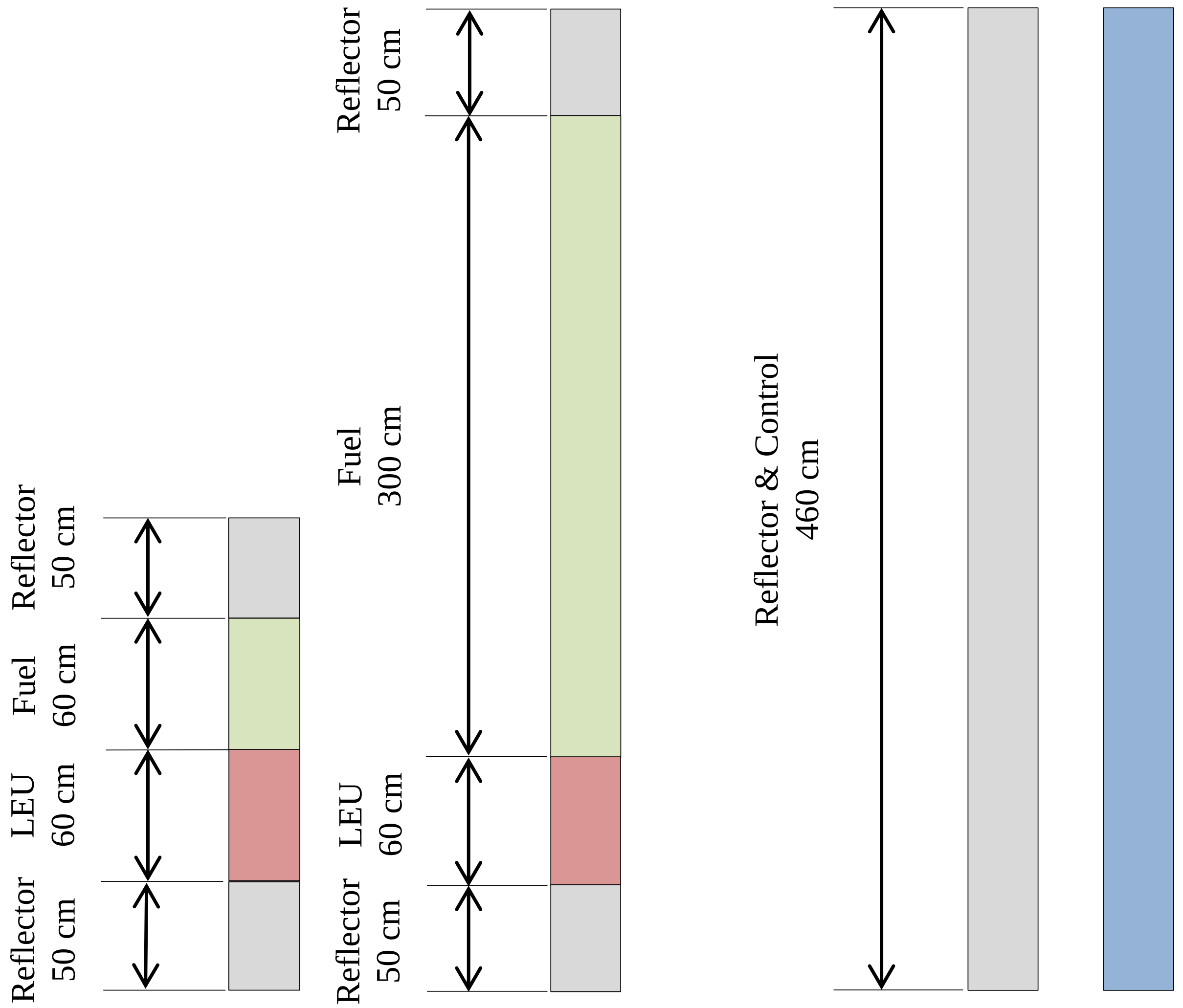


Figure 4. Assembly geometry of UCFR

II. Core Design of UCFR-100



(a) Fuel pin in UCFR-100 (b) Fuel pin in UCFR-1000 (c) Reflector pin (d) Control pin

Figure 5. Axial pin geometry

II. Core Design of UCFR-1000

Table II. Primary core design parameter

Parameters	UCFR-1000 (NU)	UCFR-1000 (SF)	UCFR-100 (NU)
Thermal power, MWth / MWe	2600 / 1000	2600 / 1000	260 / 100
Cycle Length, effective full power years	60 (Once through)	60 (Once through)	60 (Once through)
Initial heavy metal loading, t	201	216	36
Core Volume, kL	32.1	32.1	4.6
Equivalent Core Diameter, m	4.8	4.8	3.2
Fuel pin overall length, cm	460	460	260
Active core height, cm	360	360	120
Specific power density, MW/t	12.0	12.0	7.3
Volumetric power density, W/cc	81.0	81.0	56.7
Linear Power, W/cm	210.0	210.0	147.0
Fuel form	U-10Zr	SF-7Zr	U-5Zr
Fuel density, g/cc	15.98	15.91	17.38
Uranium enrichment (bottom-driver/upper-blanket), %	12.3 / NU	12.3 / Spent Fuel	11.55 / NU
Maximum Neutron Flux, #/cm^{2}sec	8.8E+15	8.7E+15	1.7E+15
Fast Neutron Fluence, #×10^{24}/cm^2	2.57	2.63	1.77
Average Coolant Velocity, m/s	4.8	4.8	1.3
Average Discharge Burnup, GWD/t / %	282.7 / 29.8	264.1 / 27.8	159.9 / 16.8

- Thermal efficiency: 38.5%
- 900K for fuel and 800K for the others were assumed

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II. Core Design of UCFR-1000

Table III. Assembly design parameters

	Driver (NU / SF / UCFR-100)			Reflector	Control
Assembly data					
-Number of pins	91	91	91	91	7
-Assembly pitch, cm	16.5	16.5	16.5	16.5	16.5
-Inter-assembly gap, cm	0.30	0.30	0.30	0.30	0.30
-Duct thickness, cm	0.30	0.30	0.30	0.30	0.30
-Gap duct and interior duct, cm	-	-	-	-	0.40
-Interior duct thickness, cm	-	-	-	-	0.30
-Interior duct inside flat-to-flat, cm	-	-	-	-	14.2
Pin data					
-Pin material and type	U-10Zr	SF-7Zr	U-5Zr	HT-9	B_4C
-Bond material	Na	Na	Na	-	He
-Active core height, cm	360	360	120	-	-
-Smeared density, % TD	74.5	74.5	75.8	-	84.3
-Cladding material	HT-9	HT-9	HT-9	-	HT-9
-Clad outer diameter, cm	1.49	1.49	1.55	1.611	5.01
-Pin pitch-to-diameter ratio	1.075	1.075	1.038	-	1.028
-Cladding thickness, cm	0.050	0.050	0.040	-	0.070
-Bond thickness, cm	0.095	0.095	0.095	-	0.2
Volume fraction at fabrication, %					
-Fuel or Absorber	43.7	43.7	49.7	-	46.6
-Bond	14.9	14.9	15.8	-	8.7
-Structure	15.7	15.7	14.3	85.7	16.6
-Coolant	25.7	25.7	20.2	14.3	28.1

III. Performance Evaluation of UCFR

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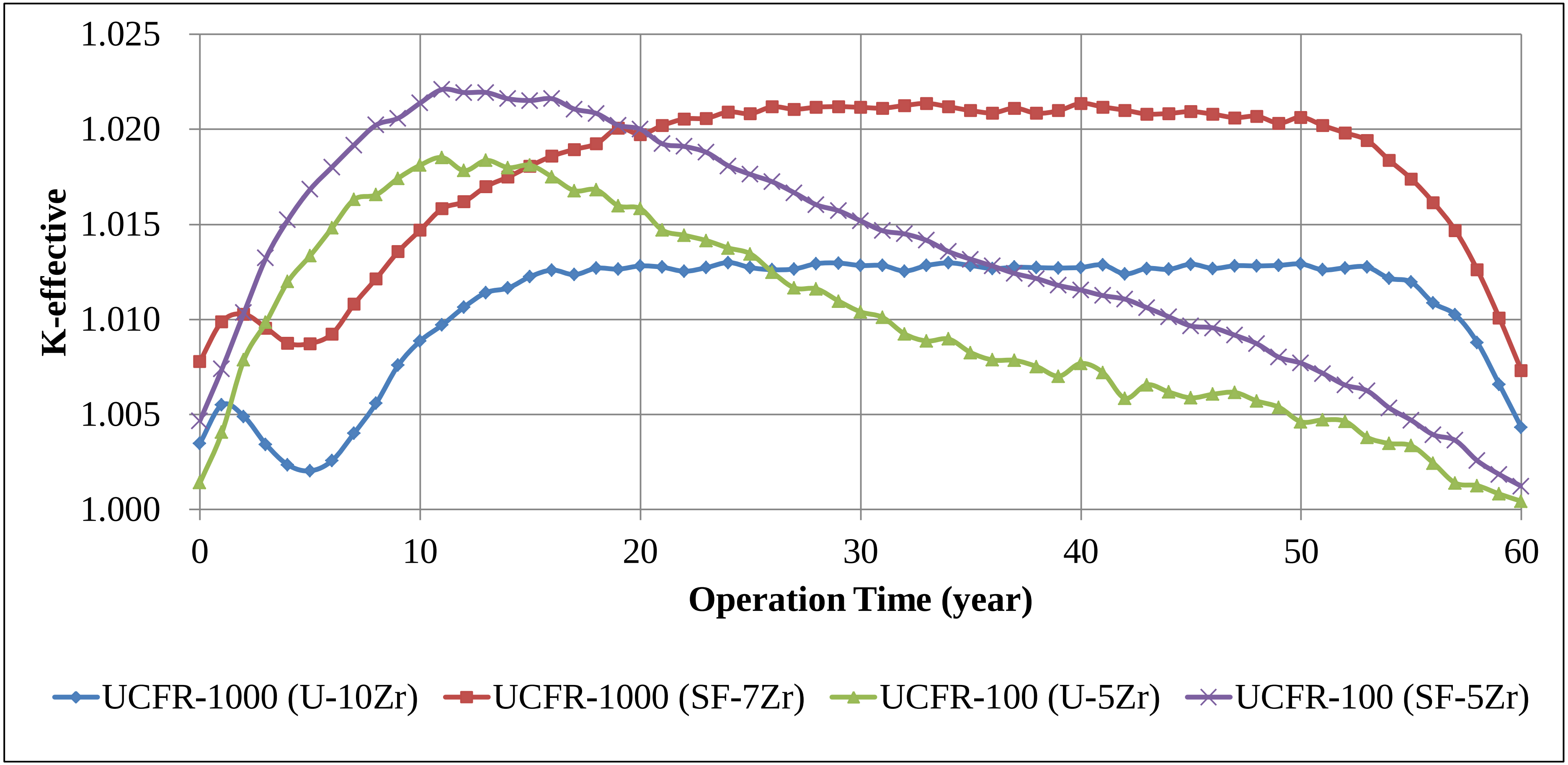

Figure 6. Keff of UCFRs

- ARO condition
- Initial slopes can be controlled by adjusting LEU

III. Performance Evaluation of UCFR

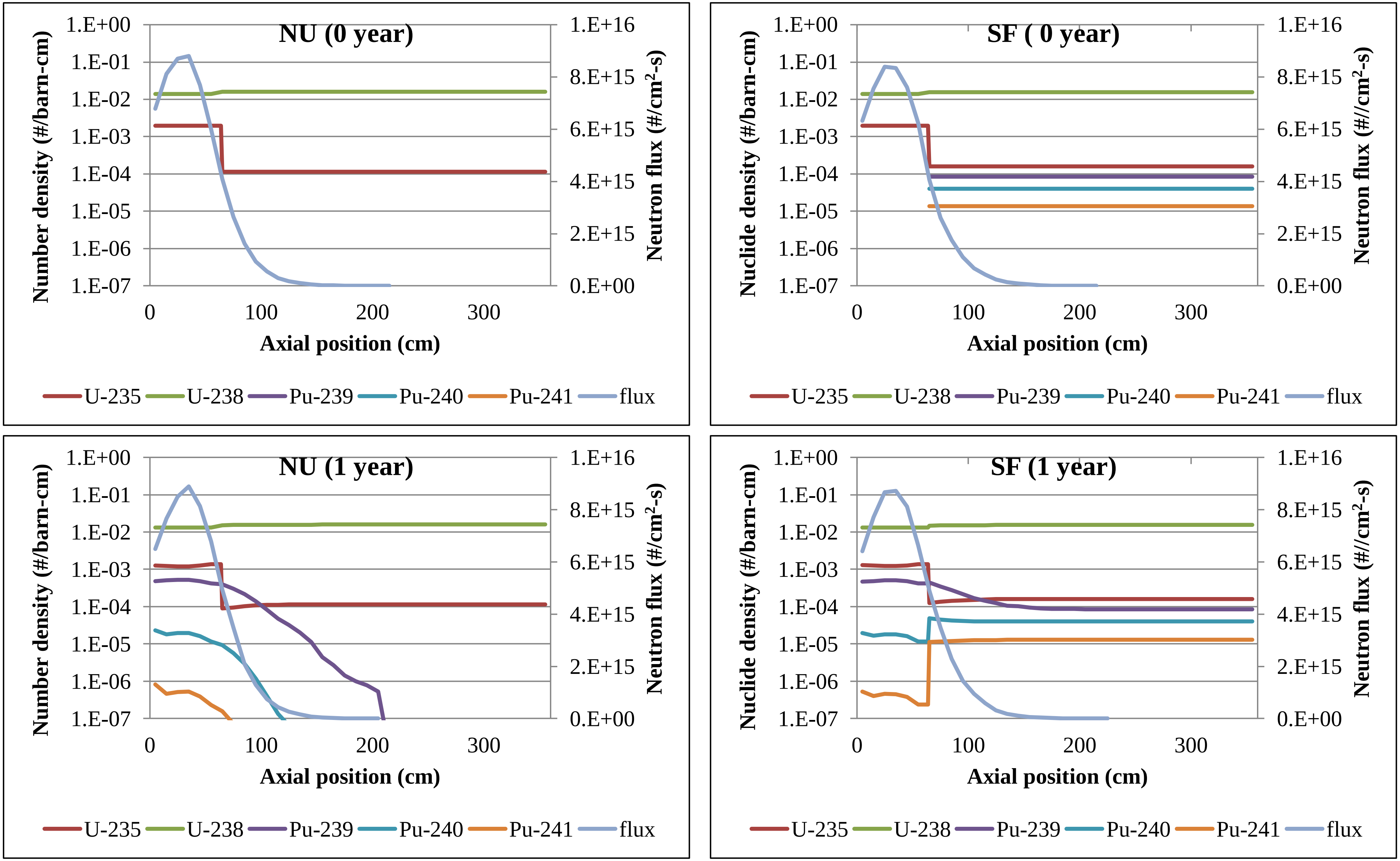

Figure 7. Nuclide isotope change of UCFR-1000 (BOC)

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III. Performance Evaluation of UCFR

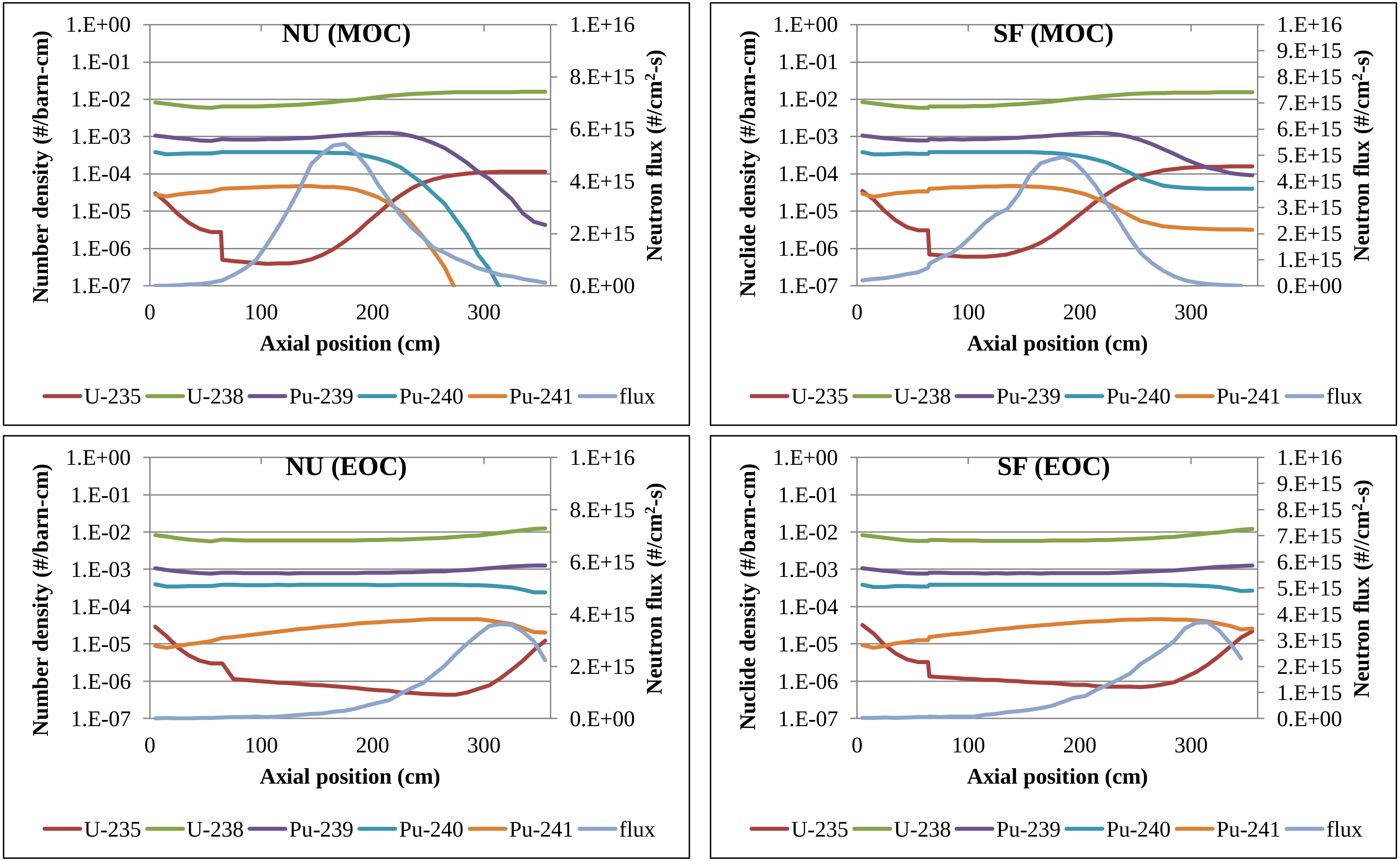
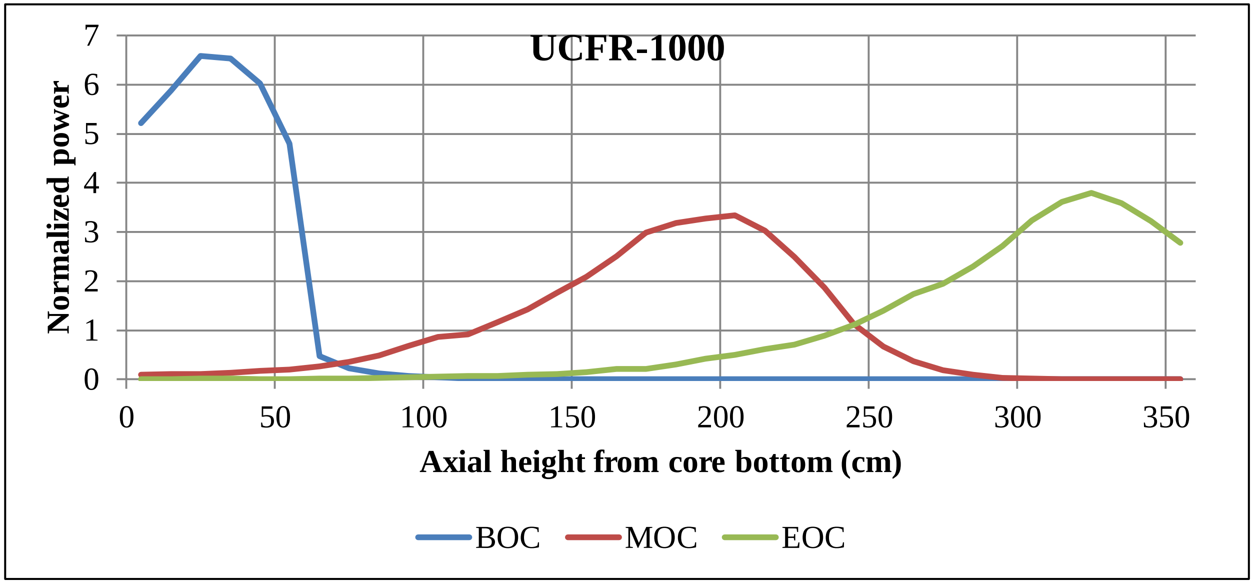


Figure 8. Nuclide isotope change of UCFR-1000 (MOC, EOC)



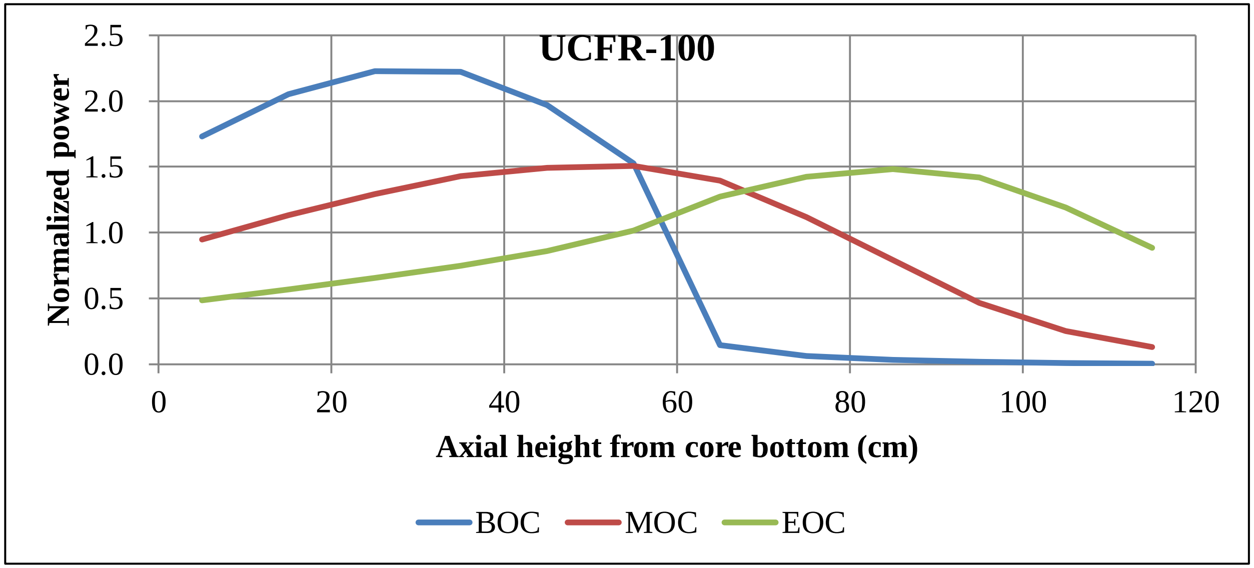
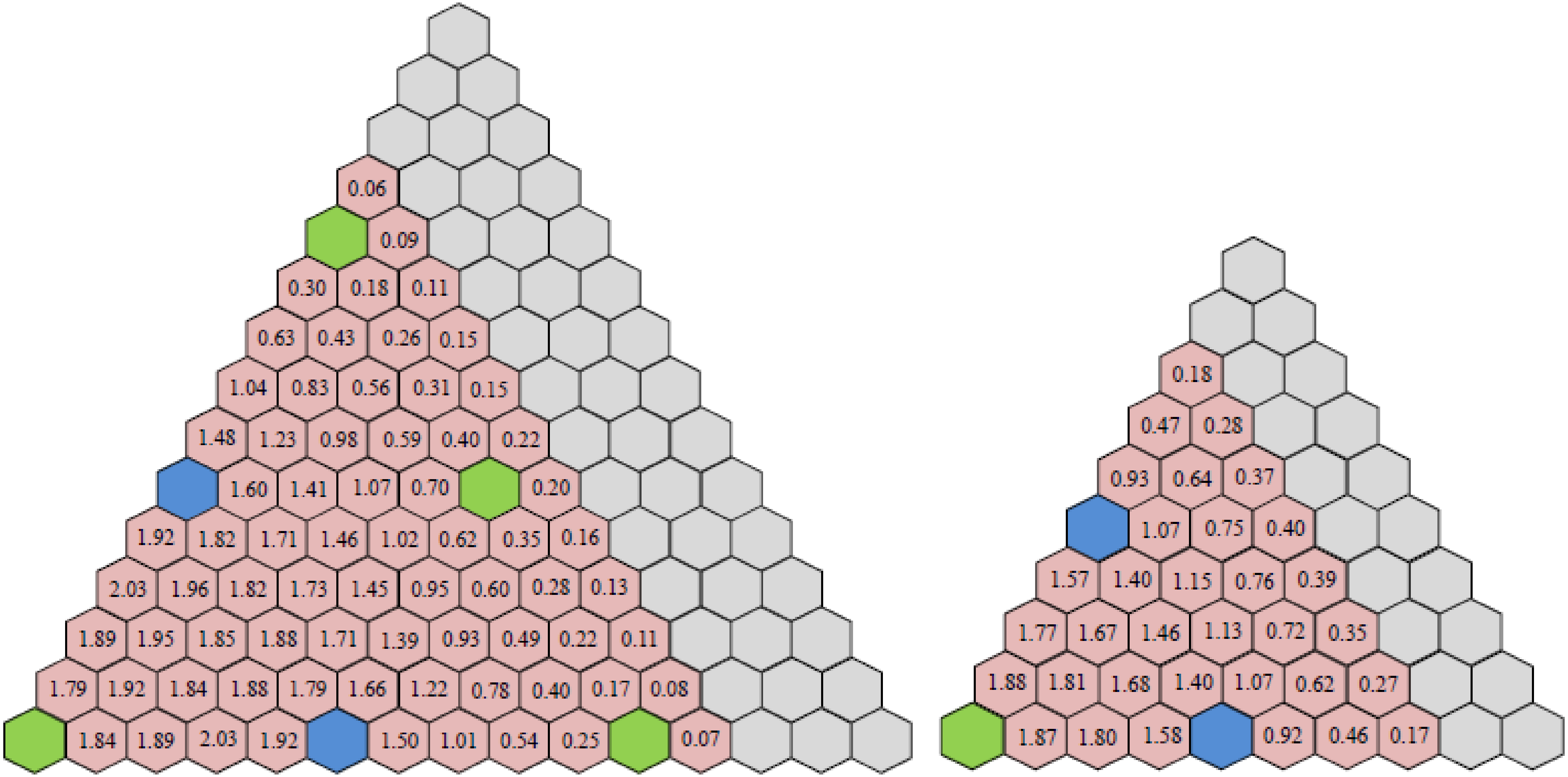
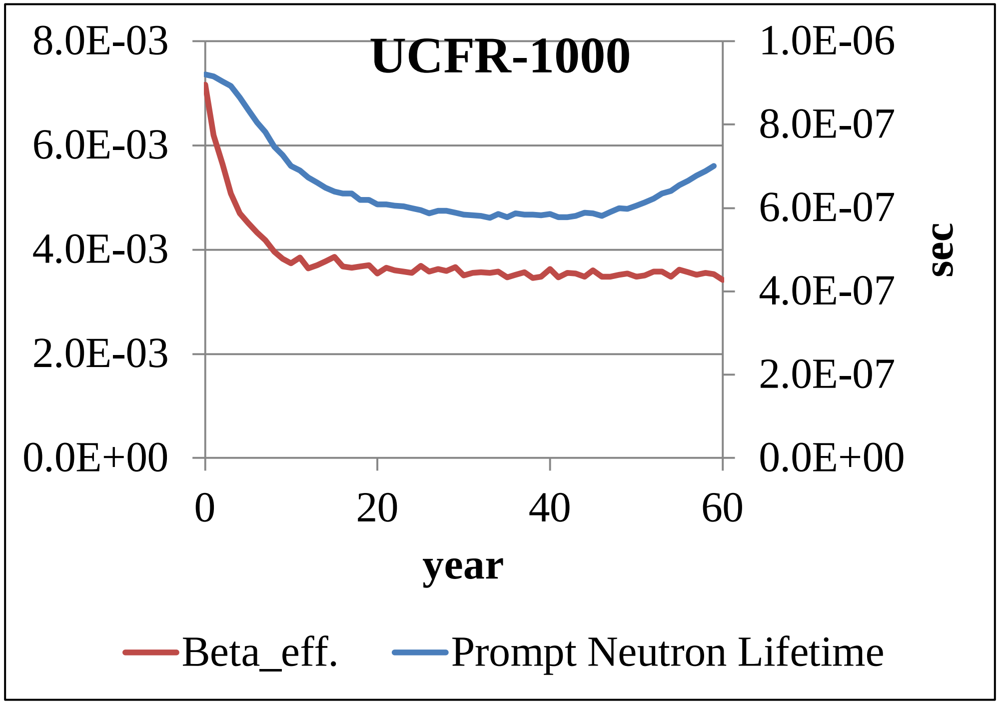


Figure 9. Normalized axial power distribution



UCFR-1000 **UCFR-100**

Figure 10. Normalized radial power distribution



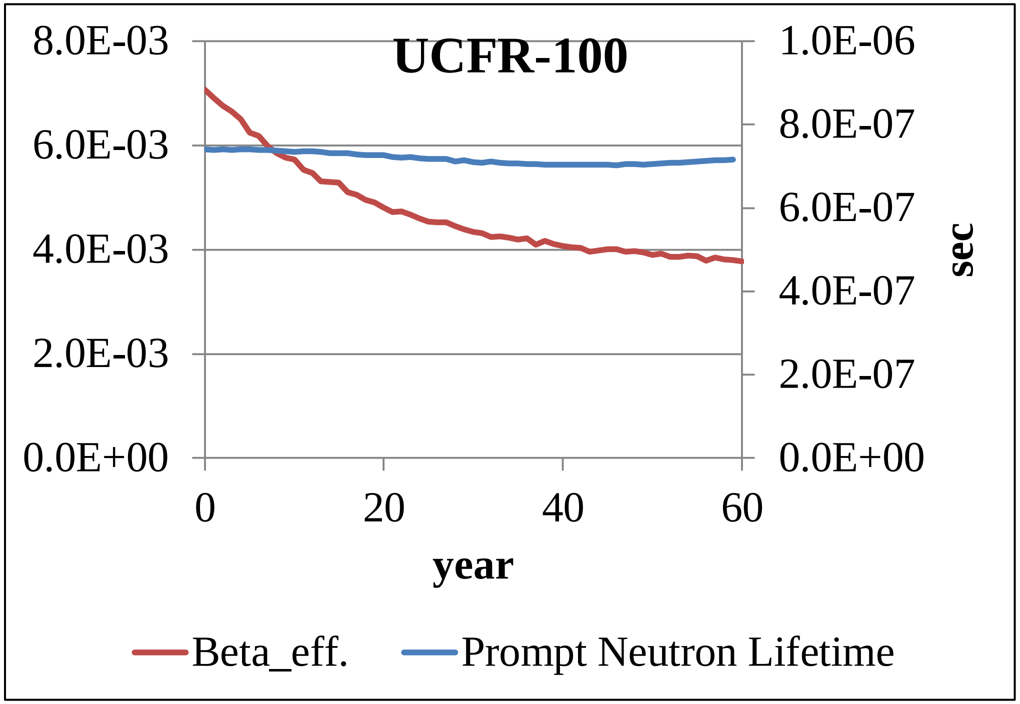


Figure 11. Effective delayed neutron fraction and prompt neutron lifetime of UCFR

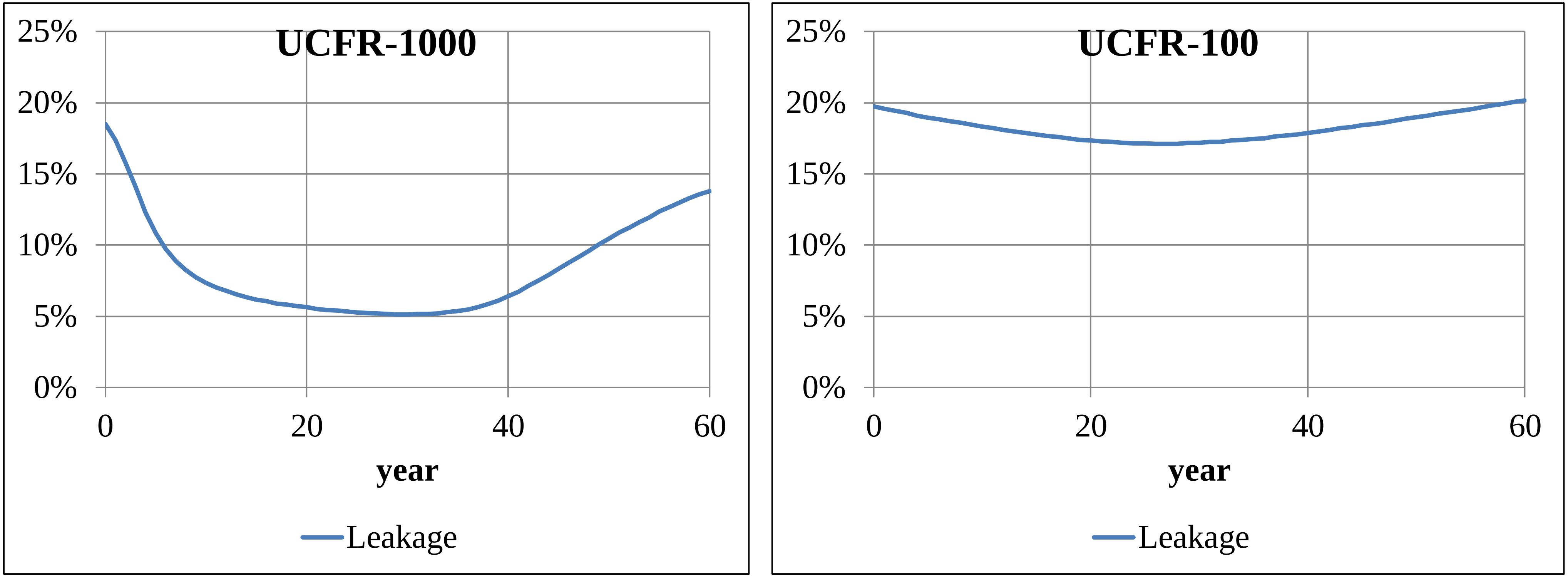
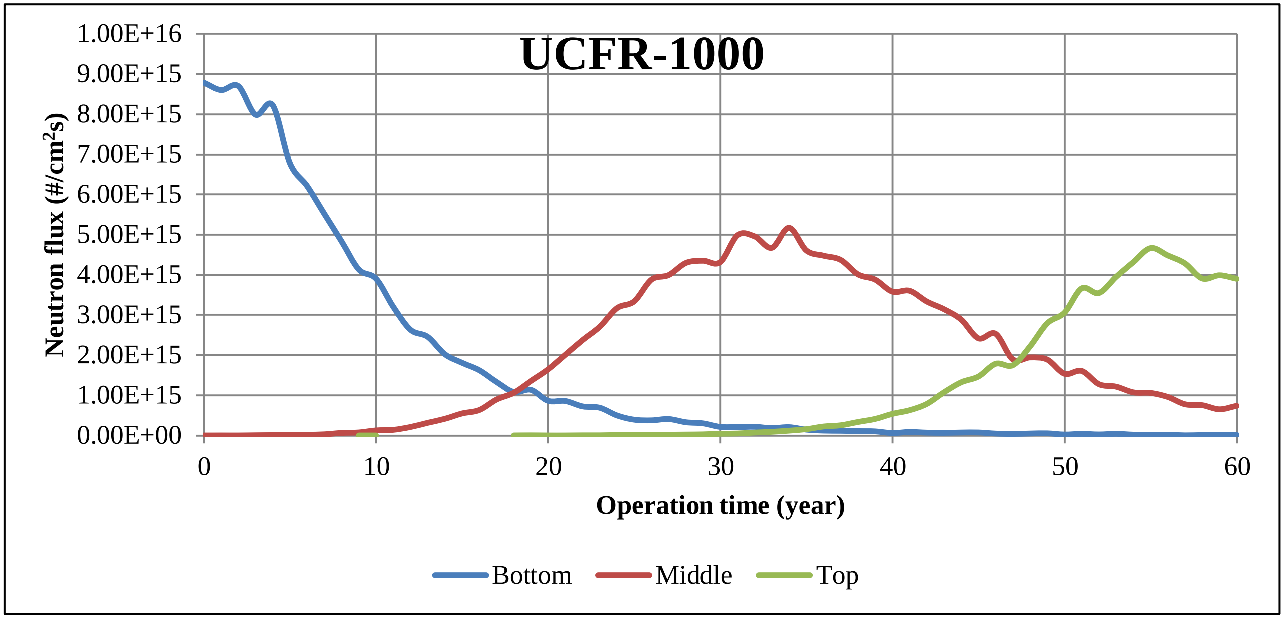


Figure 12. Neutron Leakage



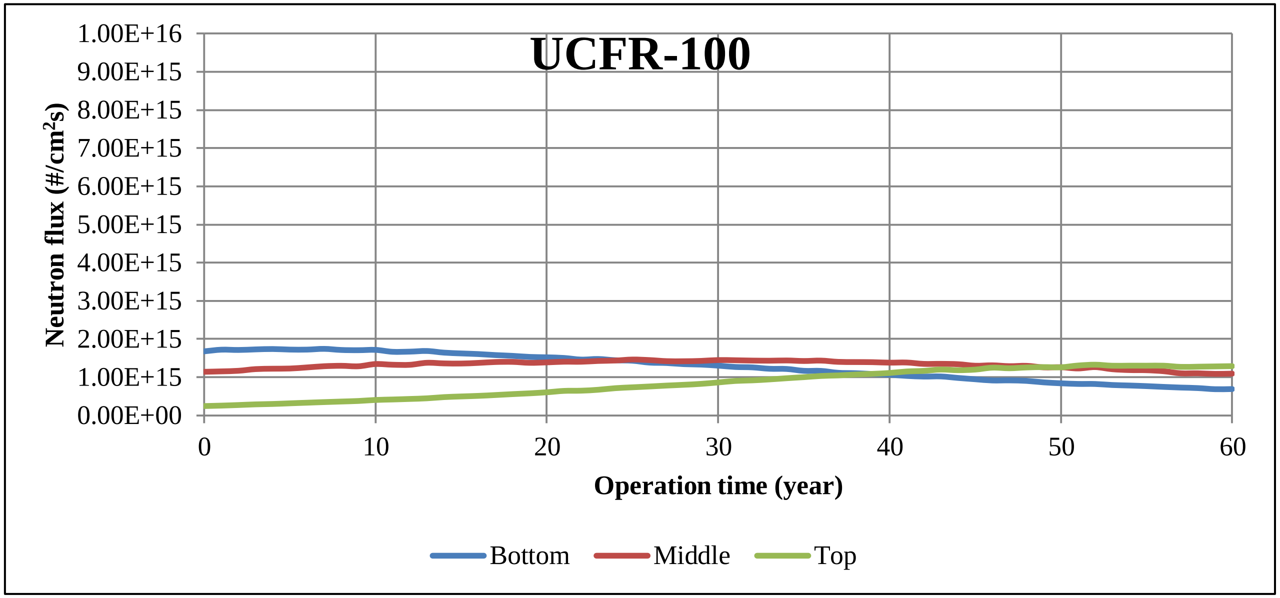
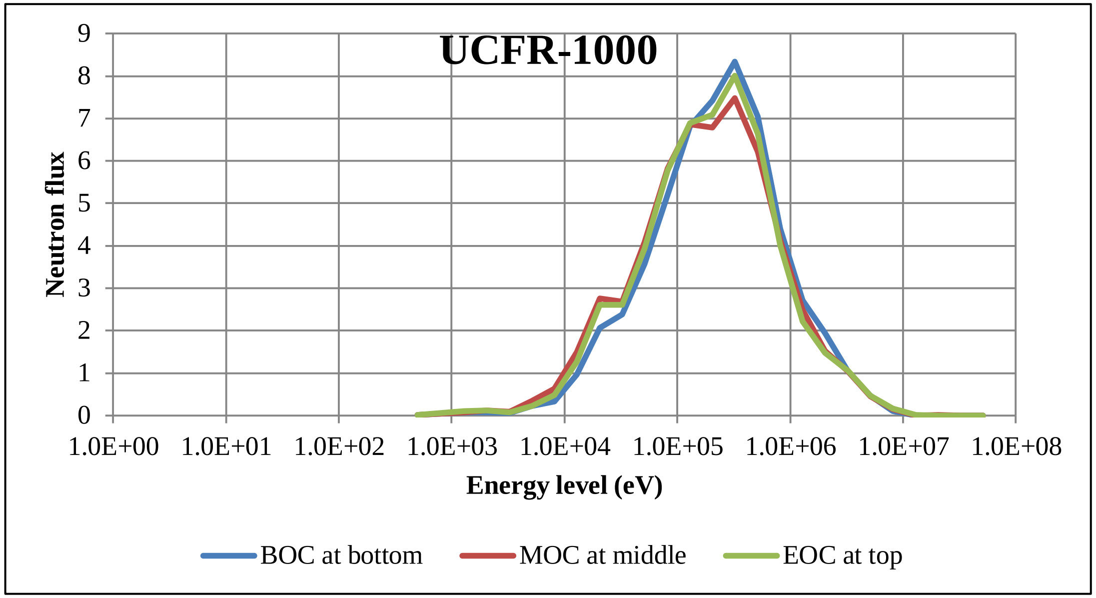


Figure 13. Neutron flux of UCFR

III. Performance Evaluation of UCFR



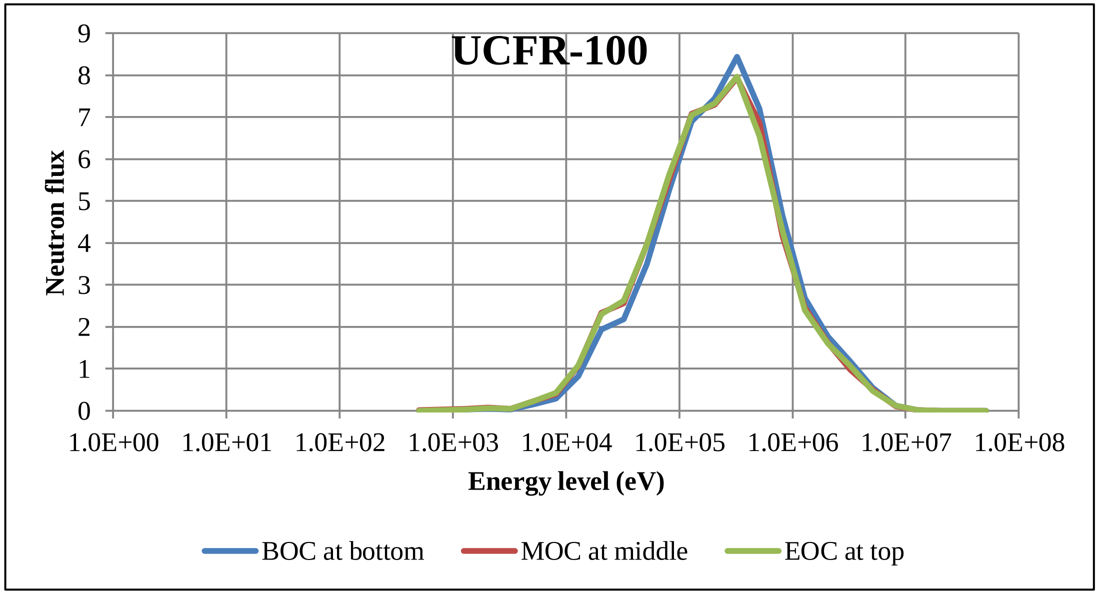


Figure 14. Energy spectrum of UCFR

Table IV. Core parameters of UCFR-1000 (NU)

Coefficients	Values (BOC/MOC/EOC)		
Delayed neutron fraction, pcm	711	359	353
Leakage, %	18.5	5.13	13.8
Total rod worth, $	8.9	17.1	16.9
ITC, pcm/K	-0.20	-0.81	-0.68
FTC, pcm/K	-0.22	-0.48	-0.54
Doppler coefficient, pcm/K	-0.72	-0.24	-0.24
Peak fluence, 10^{24} neutrons/cm^2	2.57		

Control rod worth	Values (BOC/MOC/EOC)		
Primary control assembly, $	6.1	11.0	9.9
Secondary control assembly, $	2.1	4.3	4.5
Shutdown margin, $	6.9	14.4	15.2

Cf. HT-9 irradiation experience: ~4E+23 n/cm^2

III. Performance Evaluation of UCFR

Table V. Core parameters of UCFR-100 (NU)

Coefficients	Values (BOC/MOC/EOC)		
Delayed neutron fraction (beta)	708	434	377
Leakage, %	19.8	17.2	20.2
Total rod worth, $	8.1	13.3	15.1
ITC, pcm/K	0.14	-1.18	-0.85
FTC, pcm/K	0.15	-0.90	-0.83
Doppler coefficient, pcm/K	-0.29	-0.31	-0.24
Peak fluence, 10^{24} neutrons/cm^2	1.77		
Shutdown margin, $	5.4	9.2	11.0

Cf. HT-9 irradiation experience: ~4E+23 n/cm^2

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IV. Radial Power Flattening

IV. Radial Power Flattening

- The ways for flattening radial power distribution
  1) Load Uranium-Thorium mixed fuel in the blanket of the inner core region

  2) Increase the zirconium fraction of the blanket in the inner core region

  3) Decrease the fuel diameter in the inner core region

  4) Increase the distance between the fuel and the duct of the blanket in the inner core region

IV. Radial Power Flattening

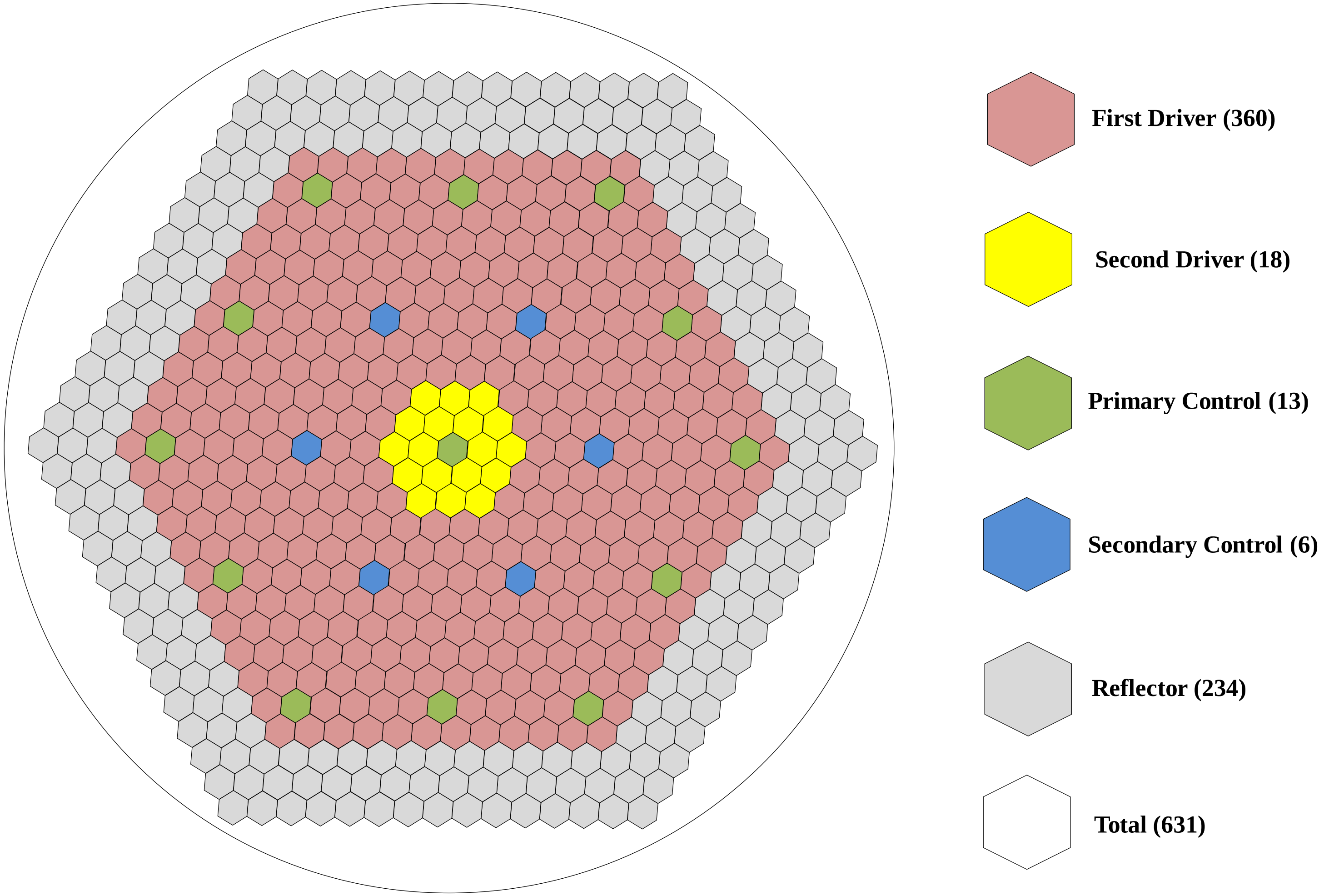

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Figure 15. Core layout of UCFR loading thorium fuel in inner core

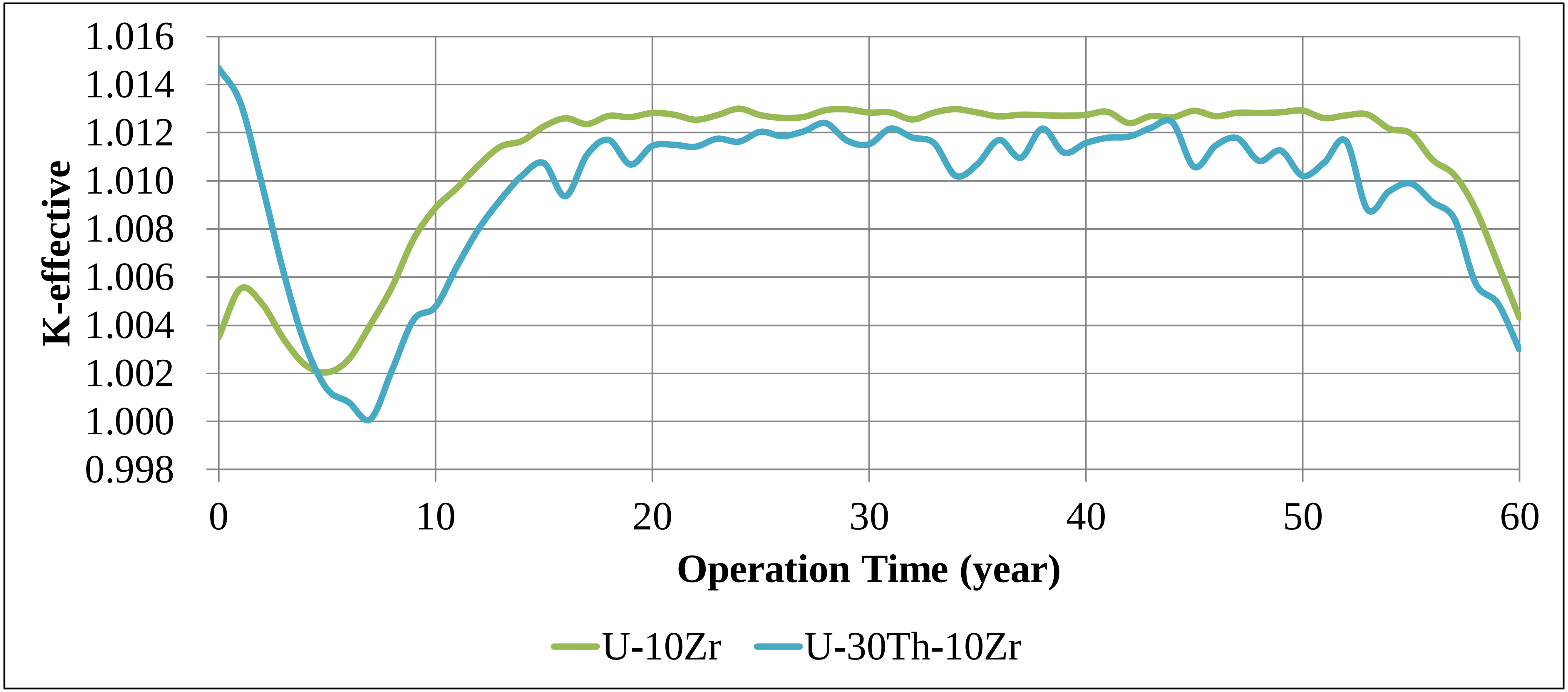

Figure 16. Keff of UCFR loading thorium fuel in inner core

Table VI. Reactivity Coefficients of UCFR-1000 Pin & Assembly

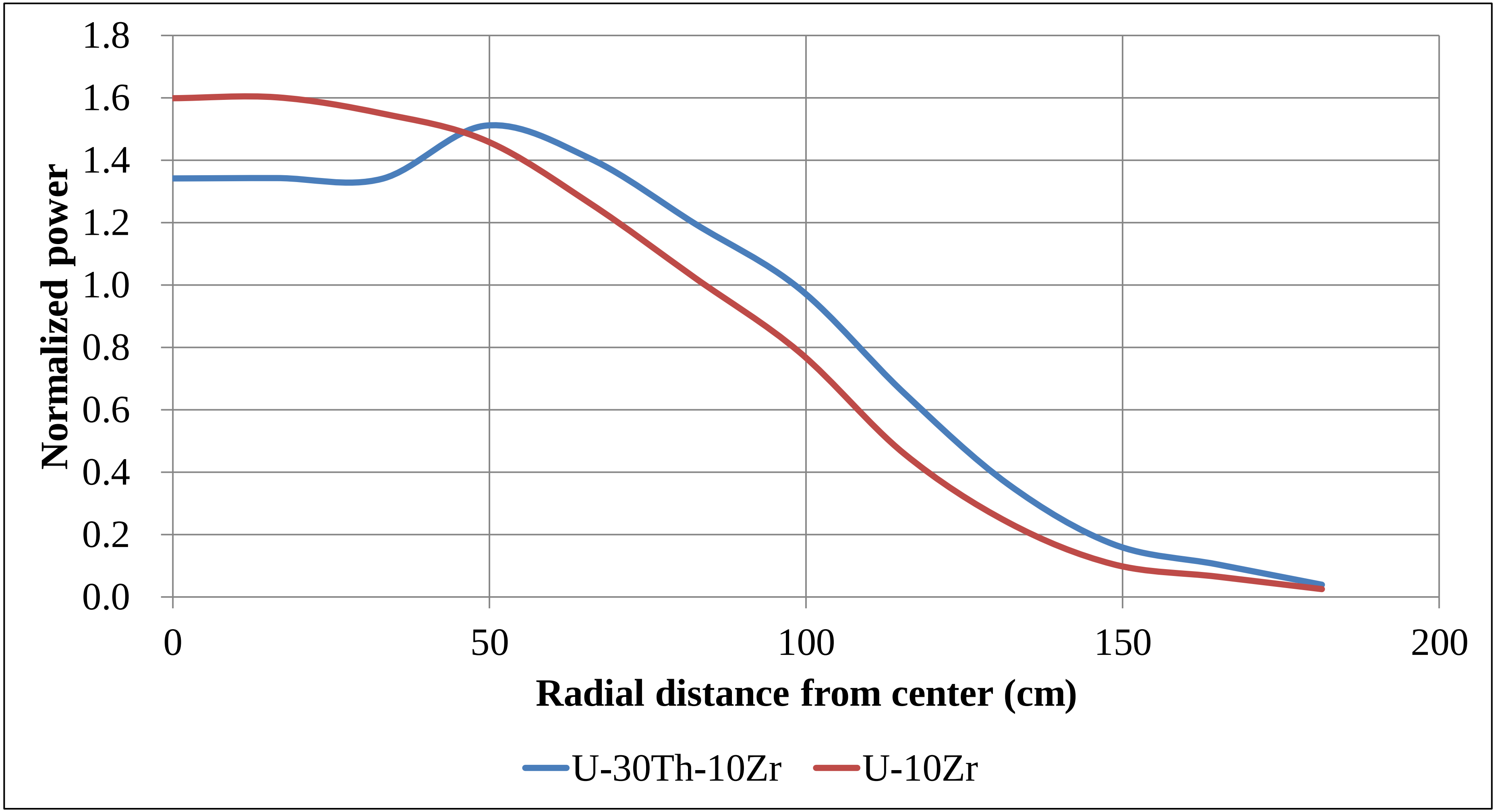

Figure 17. Normalized radial power distribution (MOC)

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IV. Conclusion and Future Work

V. Conclusions and Future Work

- Core designs of UCFR-1000(NU/SF) and UCFR-100(NU) have been developed.
- Core performance evaluation and safety parameter analysis is underway
- Radial power flattening is under way
- Further analysis of UCFR-100 with spent fuel
- UCFR with venting region instead of reflector
- Detail reactivity analysis

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