A Preliminary Study of Autonomous and Ultra-long Life Hybrid Micro-modular Reactor Cooled by Sodium Heat Pipes

KAIST

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Introduction

❖ **The 2030 Agenda for Sustainable Development**

➢ 7. Affordable and clean energy - targets and indicators

- By 2030, increase substantially the share of renewable energy in the global energy mix (target 7.2).
- International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems (indicator 7.A.1).

➢ 13. Climate action - progress of goal 13 in 2019

- With rising greenhouse gas emissions, climate change is occurring at rates much faster than anticipated and its effects are clearly felt worldwide.
- Increasing greenhouse gas emissions are driving climate change.

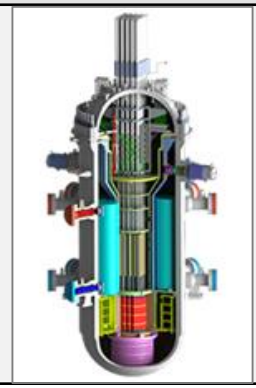
https://sustainabledevelopment.un.org/

Introduction

❖ Sustainable Development in Nuclear Energy

➢ Increase of the interest in SMRs

SMRs
(small and medium sized or modular reactors)



- wide range of applications
- possibilities for cogeneration
- non-electrical applications
- inherent passive safety
- reduced upfront capital investment
- flexible power generation

➢ Hybrid system with nuclear power plant

Solar Thermal Power
(Concentrated Solar Power)

Advantages	Disadvantages
• Zero CO_2 emissions • Sustainable and continuous solar energy	• Low efficiency • Requires large area • Intermittency

Nuclear Power Plant
(Large-scale nuclear power)

Advantages	Disadvantages
• Zero CO_2 emissions • High efficiency • Continuous, steady operation	• Hardly use to load-follow • Limitation of the location

Energy Storage System
(Thermal energy storage)

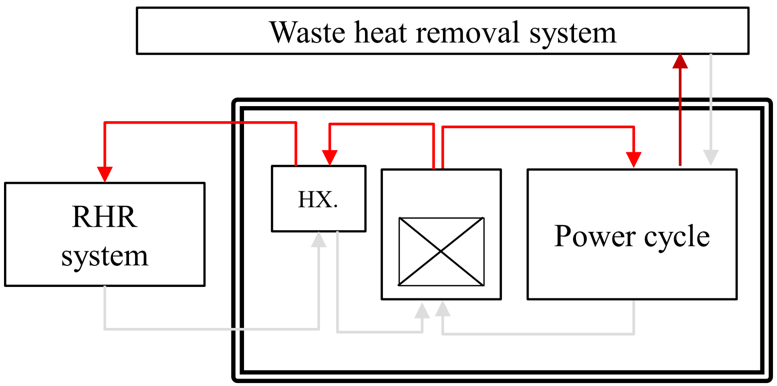
Advantages	Disadvantages
• Storage and supplement the surplus energy	• Requirement of large capacity

Introduction

❖ Objective

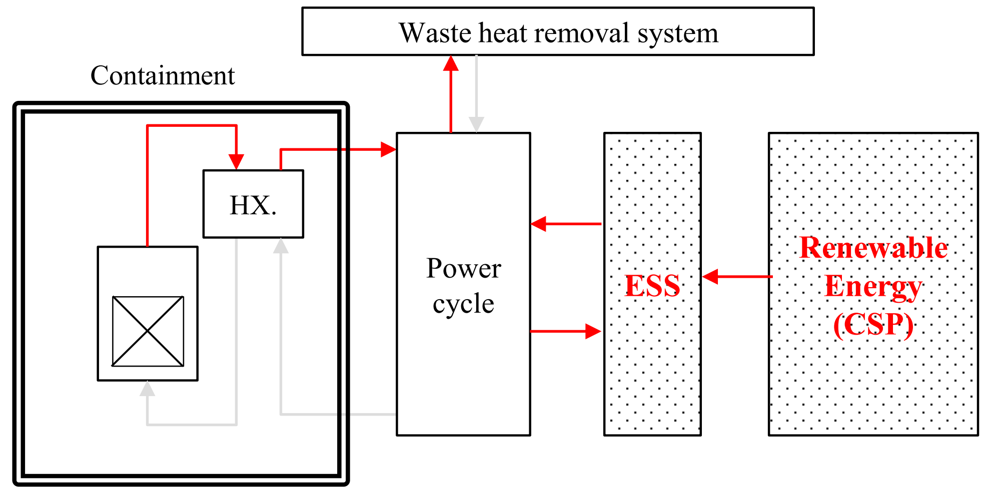
➢ Development of highly safe autonomous micro modular reactor and renewable hybrid technology

KAIST-MMR



➢ 10MW$_e$ micro-sized nuclear fast reactor
➢ Supercritical CO_2-cooled Brayton cycle
➢ Long lifetime (20 years)
➢ Transportable, passive safety system

H-MMR



➢ Combining modified MMR with ESS and renewable energy
➢ Autonomous reactor for load following
➢ Heat pipe cooled passive system

→ Hybrid load following system through autonomous operation with MMR and ESS

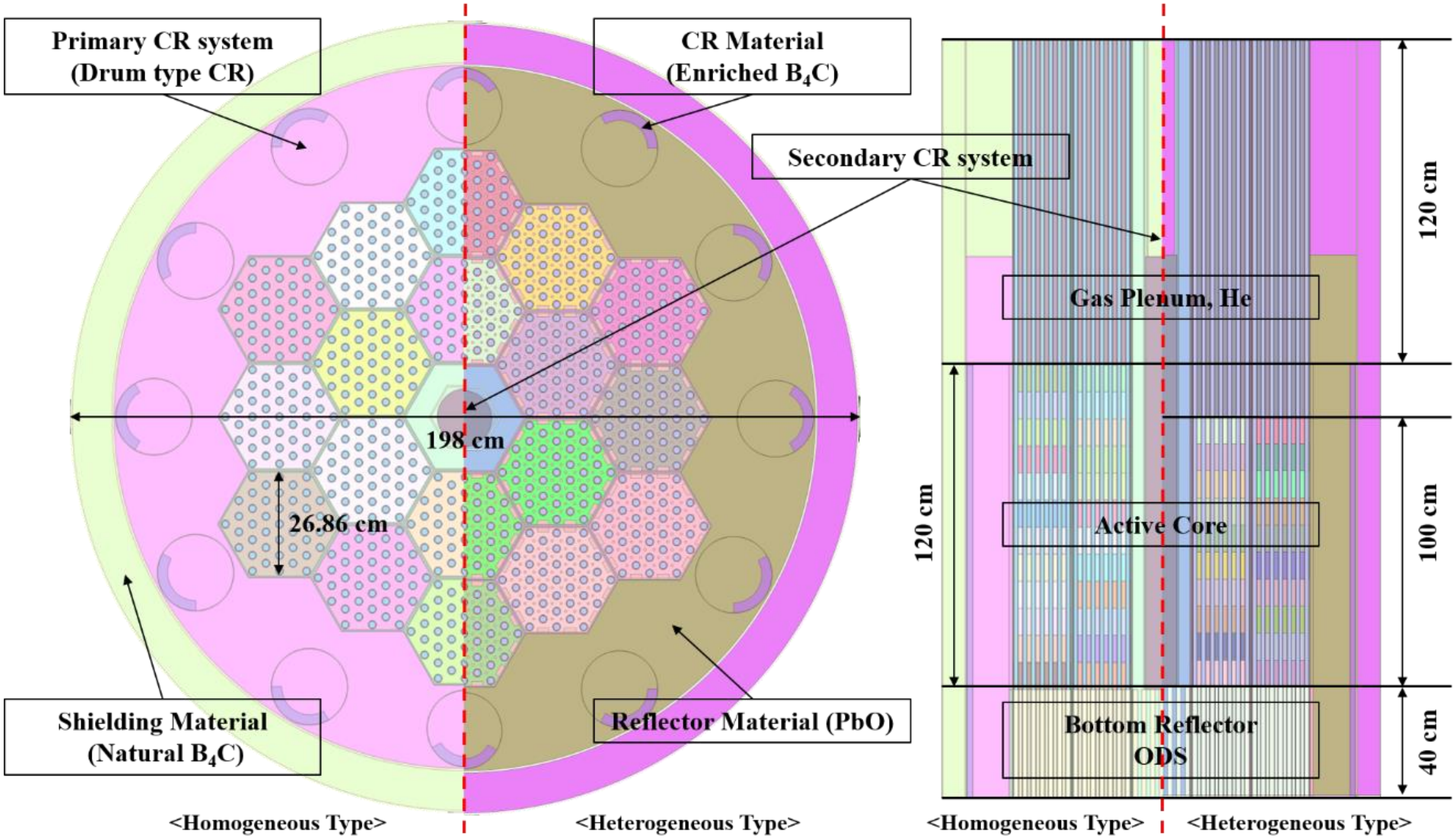
Conceptual Design of the H-MMR

Oxide dispersion strengthened alloys (ODS)

❖ H-MMR design

➢ H-MMR core configuration

- Inserting graphite moderator to mitigate the conversion.
- Reduced core height in heterogeneous type to allow leakage to axial direction.



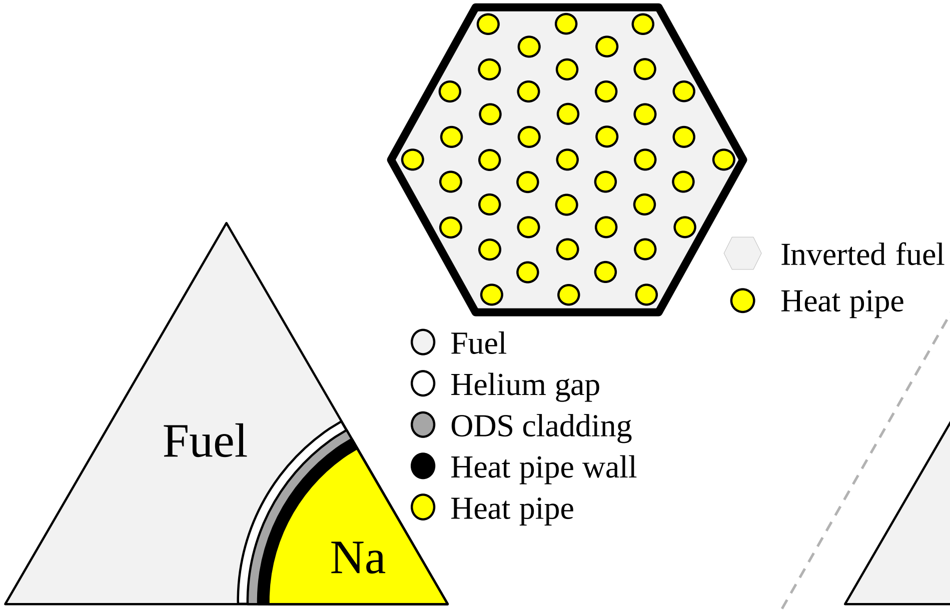
Conceptual Design of the H-MMR

❖ H-MMR design

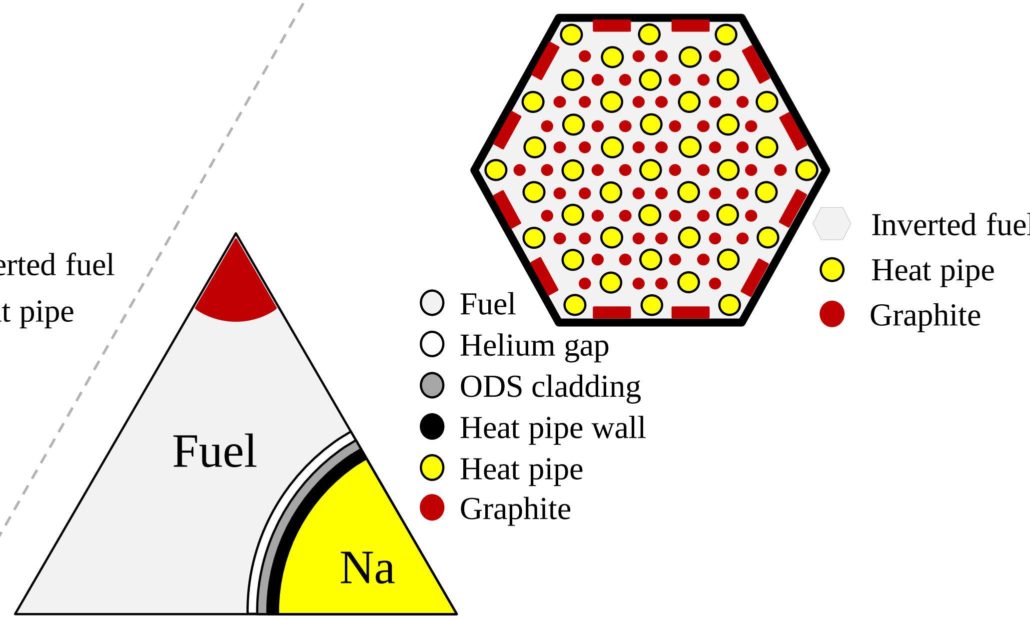
➢ H-MMR design parameters

Parameters	Values
Reactor power	12 MWth
Number of fuel assemblies	18
Active core equivalent radius / hom. height / het. height	61.46 cm / 120 cm / 100 cm
Whole core equivalent radius / height	99 cm / 280 cm
Hom. / het. mass of U	9.82 ton (545.54 kg/FA) / 8.71 ton (483.67 kg/FA)
Power density	8.89 W/cc

➢ Inverted fuel assembly (IFA) designs



<Homogeneous Type>

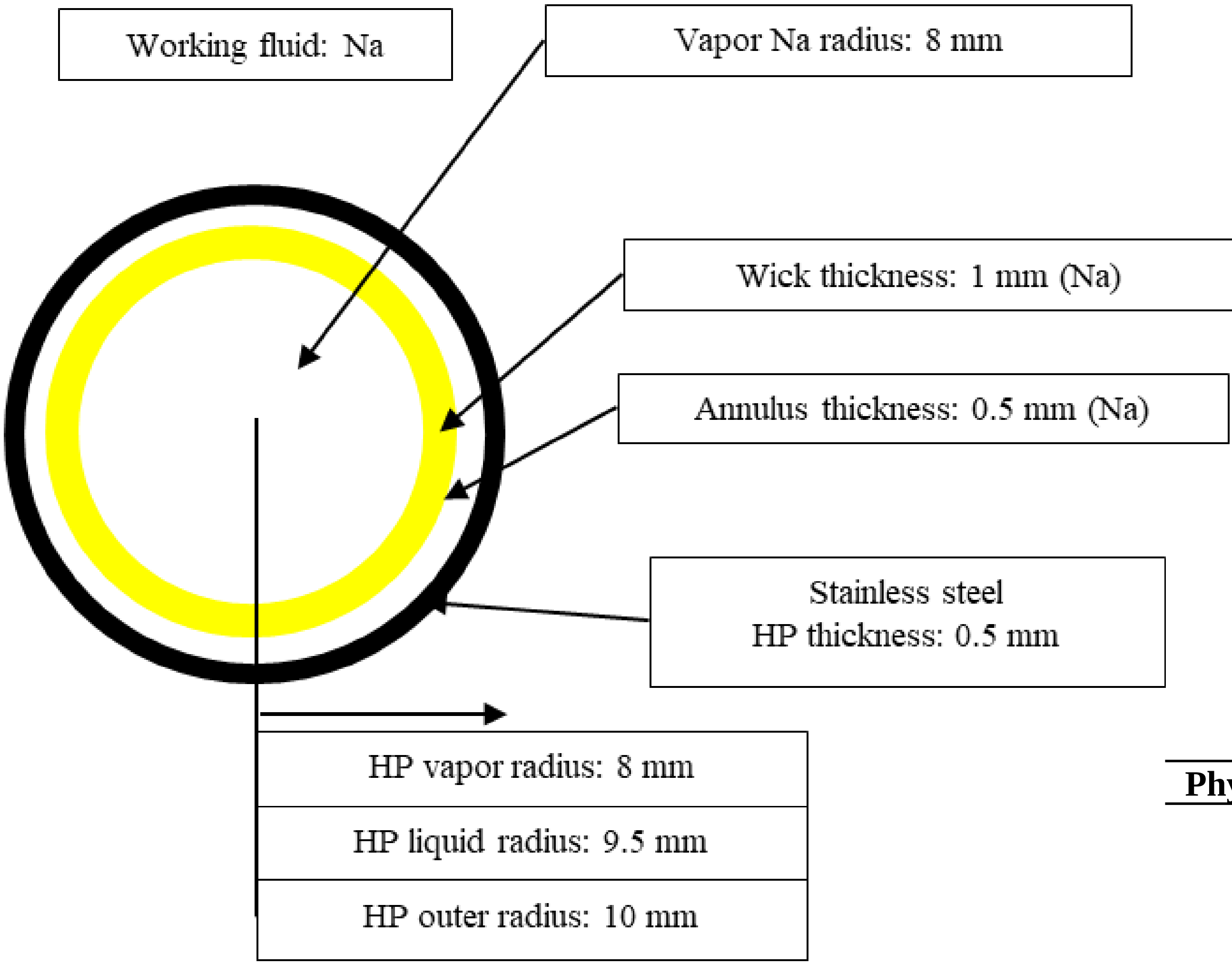


<Heterogeneous Type>

Conceptual Design of the H-MMR

❖ H-MMR design

➢ Design of heat pipe (capillary-wicked heat pipe)



Physical properties	Values
Phase at STP	Solid
Melting point	370.94 K
Boling point	1156.09 K
Density	0.968 g/cc 0.927 g/cc (at m.p)

Conceptual Design of the H-MMR

❖ H-MMR design

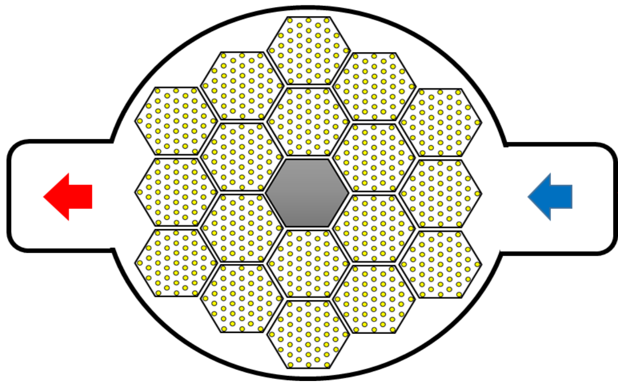
➢ Design parameters of IFA

Parameters	Homogeneous Type	Heterogeneous Type
Fuel material (density)	$U^{15}N$ + C (11.53 g/cc)	$U^{15}N$ (13.5 g/cc)
Fuel volume fraction	82.5% ($U^{15}N$) / 17.5% (C)	87.8% ($U^{15}N$) / 12.2% (C)
Fuel enrichment (^{235}U)	11.67 w/o	11.60 w/o
Graphite moderator (rectangle/circle, radius)	-	2.95 cm × 1.00 cm / 0.31 cm
N-15 enrichment	99.9 %	
Cladding material (density)	ODS (7.2 g/cc)	
Gap material	Helium	
Number of heat pipes	43	
Heat pipe radius	0.95 cm	
Heat pipe wall thickness	0.05 cm	
Heat pipe cladding thickness	0.05 cm	
Heat pipe gap thickness	0.01 cm	
Fuel assembly pitch	26.86 cm	
Fuel assembly duct thickness	0.3 cm	
Inter-assembly gap	0.25 cm	
Average fuel temperature	1290 K	
Average heat pipe temperature	1122 K	

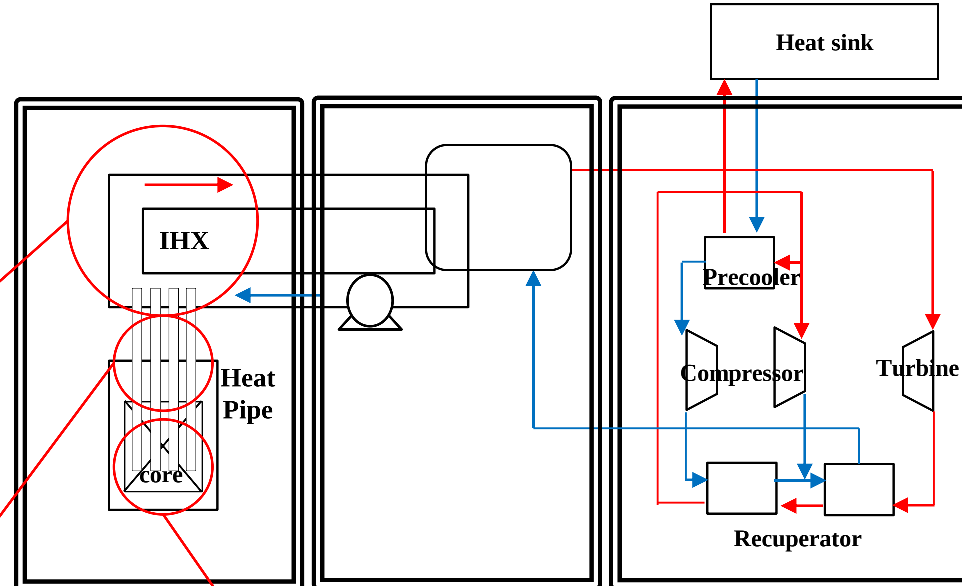
Conceptual Design of the H-MMR

❖ H-MMR design

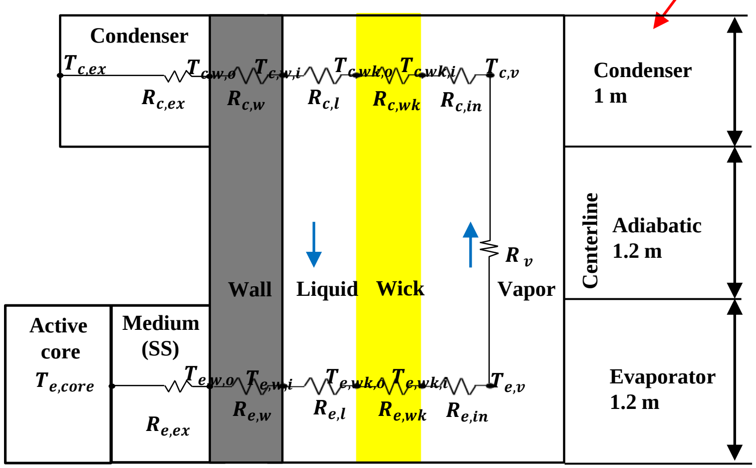
➢ H-MMR heat pipe heat exchanger



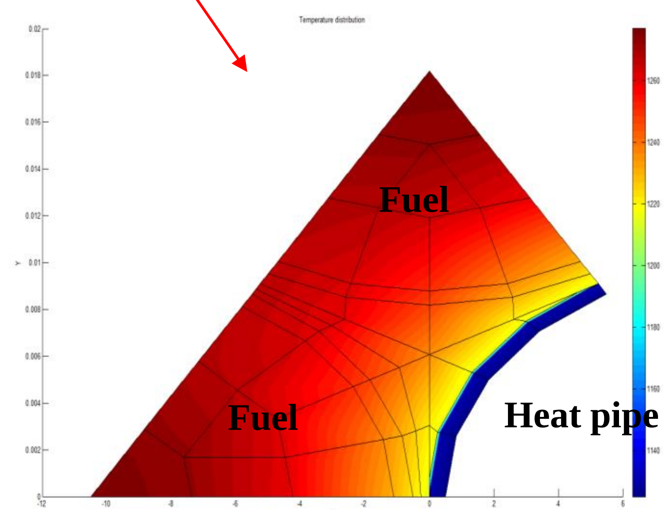
<Intermediate Heat Exchanger (IHX)>



< Hybrid micro modular reactor (H-MMR) >



<1D thermal resistance of heat pipe>



< FEM sub-channel analysis)>

Conceptual Design of the H-MMR

❖ H-MMR design

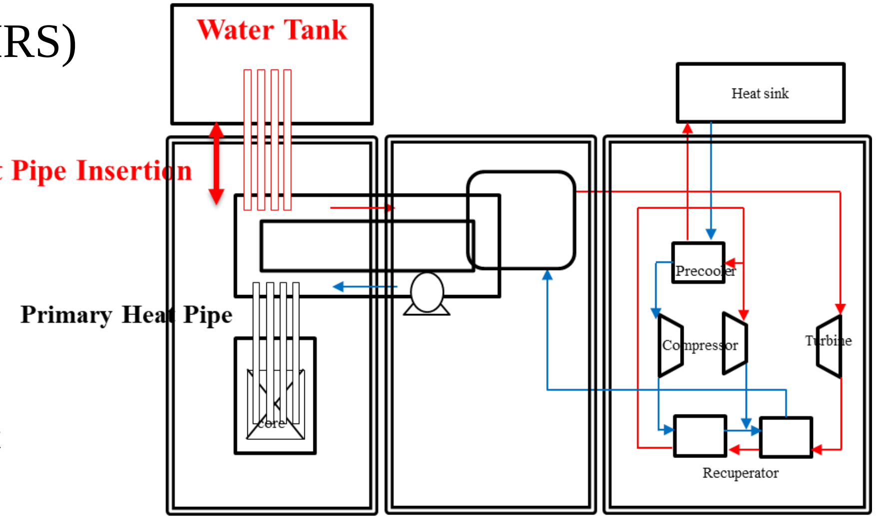
➢ Temperature distribution in IFA

Parameters	Homogeneous Type	Heterogeneous Type
Max. temp. of fuel	1594.44 K	1383.18 K
Avg. temp. of fuel	1290.83 K	1197.24 K
Avg. temp. of gap	1067.54 K	1059.79 K
Age. temp. of clad	965.89 K	965.41 K
Avg. temp. of duct	1392.13 K	1301.59 K
Avg. temp. of bar type moderator	-	1369.39 K
Avg. temp. of pin type moderator	-	1214.40 K

➢ Heat pipe residual heat removal system (HP-RHRS)

- 430 kWth heat removal during accident
- Primary heat pipe: sodium
- Intermediate heat exchanger(IHX): liquid metal
- Secondary heat pipe: water
- Heat sink: water tank

- Active core → primary heat pipe → intermediate heat exchanger (IHX)→ secondary heat pipe → heat sink



< Residual Heat Removal System of H-MMR>

Conceptual Design of the H-MMR

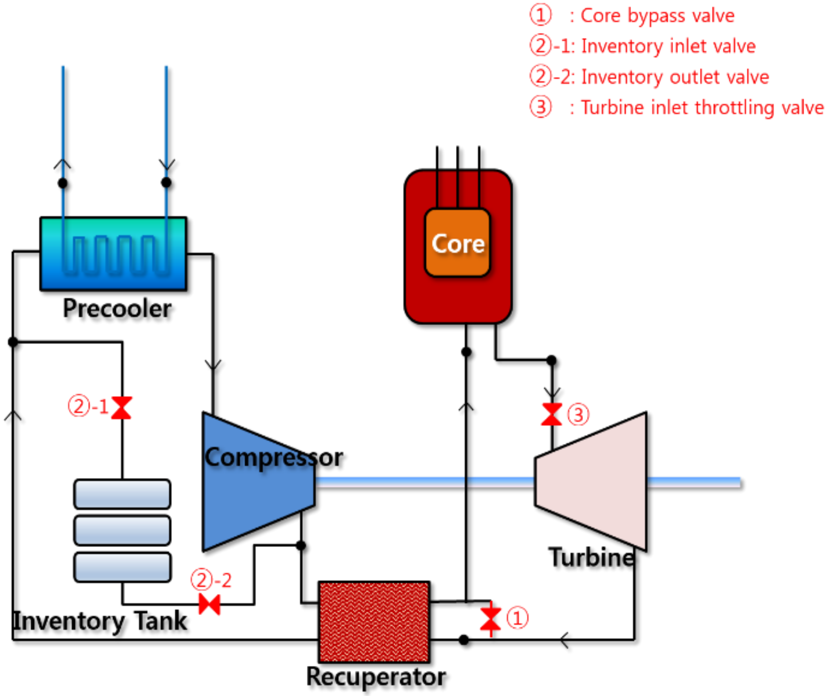
❖ Passively Autonomous Load-follow Operation (PLFO)

➢ Definition of PLFO

- Load-follow operation without any control in reactor core

➢ Three methods to control mass flow rate

- Core bypass control method
  - Control the system mass
  - Well-known for high cycle efficiency
- Mass inventory control method
  - Control the system mass
  - Relatively slow
- Turbine throttling control method
  - Forced pressure drop at the turbine inlet

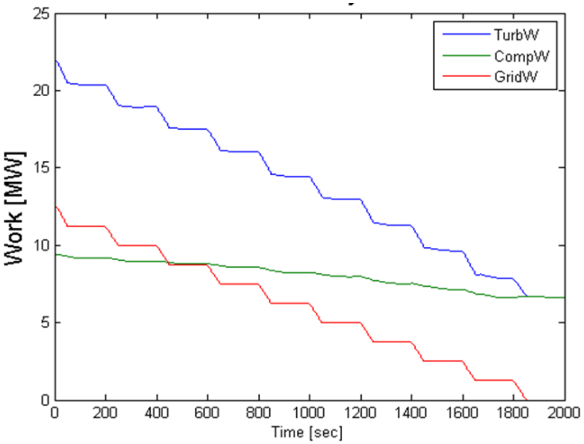


❖ Passively Autonomous Load-follow Operation (PLFO)

➢ PLFO of previous KAIST-MMR

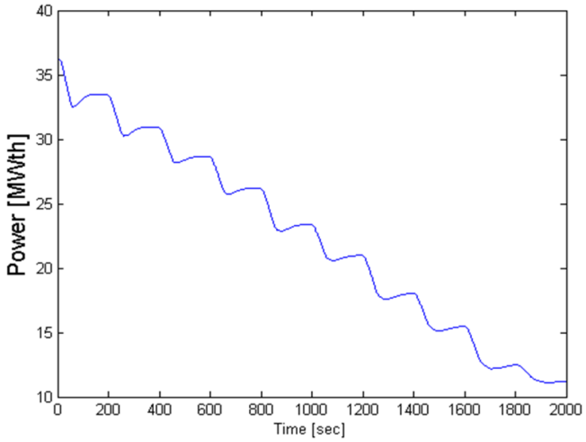
- Based on cycle efficiency, combination of core bypass and mass inventory is used.

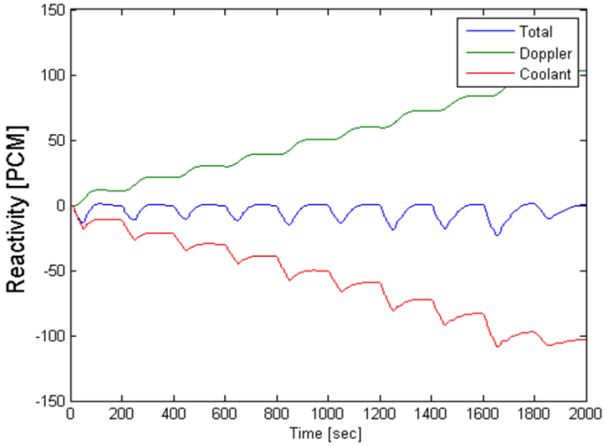
Condition	FTC, pcm/K	CTC, pcm/K	CVR, pcm
BOL	-0.457 ± 0.02	-0.490 ± 0.17	-234.470 ± 16.8
EOL	-0.479 ± 0.03	-0.630± 0.18	-352.614 ± 17.0

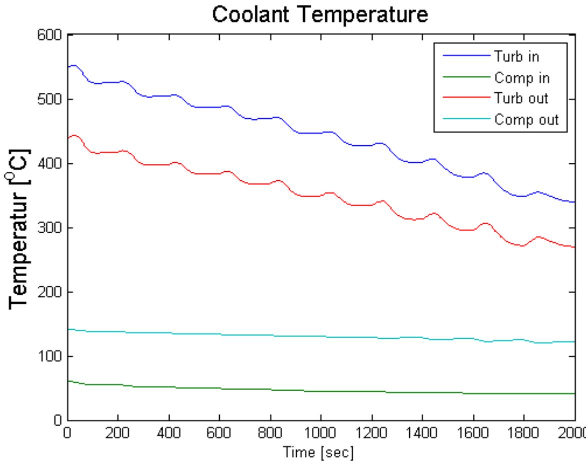


➢ Results of part PLFO of KAIST-MMR

- Autonomous core bypass and mass inventory control system.
- Linear step change (10%) of grid demand and turbomachinery's work
  - Grid demand change : 100 % to 0 %



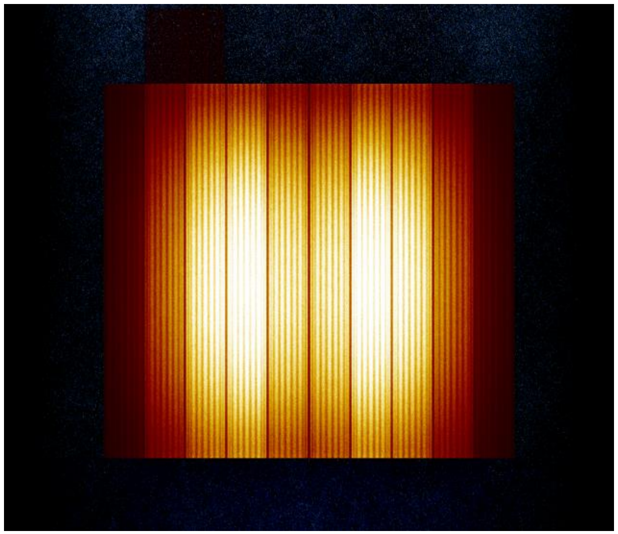
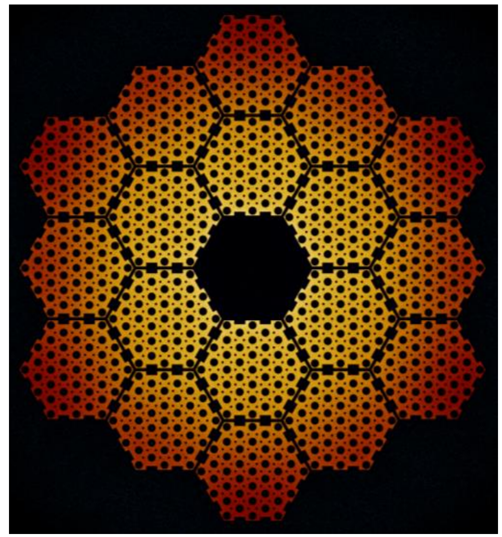
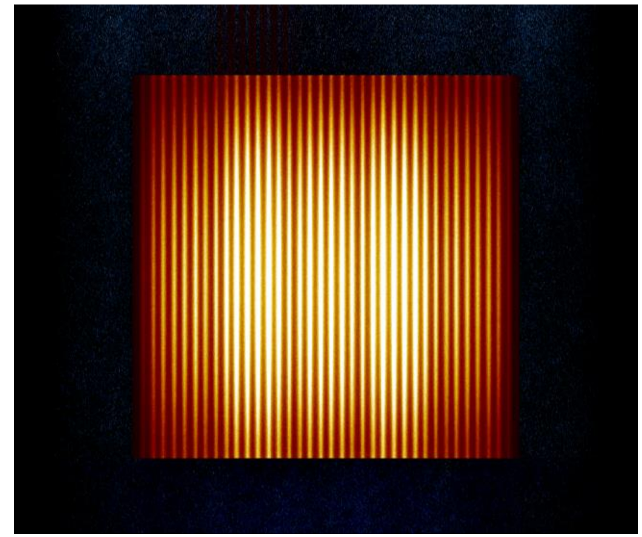




Numerical Results

❖ Neutronic analysis method

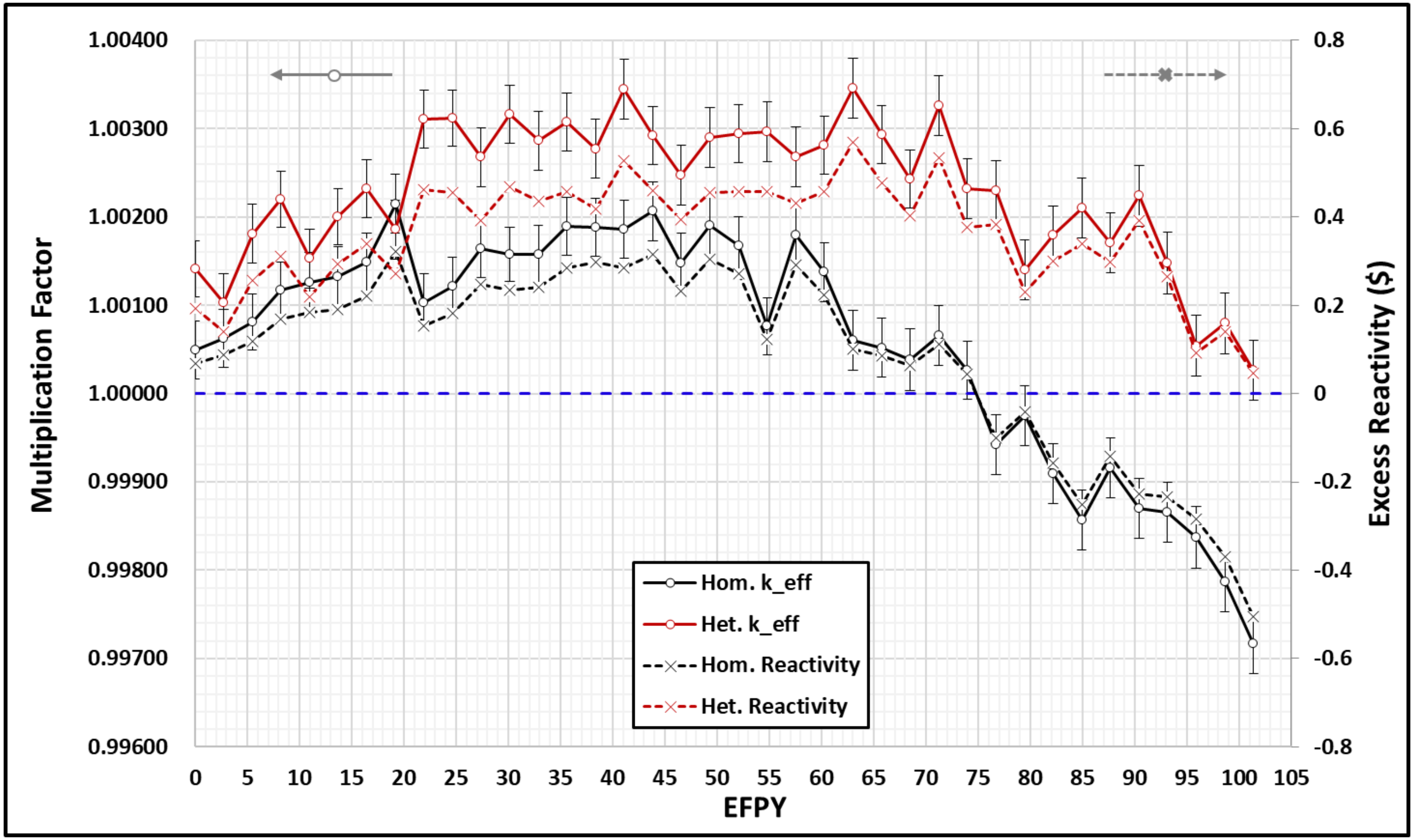
➢ Serpent 2 Monte Carlo code

- ENDF/B-VII.1 library
- Burnup calculation: 50,000 neutron histories / 300 active cycle / 200 inactive cycle (with FA-wise node divided by 10 cm height)
- Feedback coefficient calculation: 1M neutron histories / 300 active cycle / 200 inactive cycle

Numerical Results

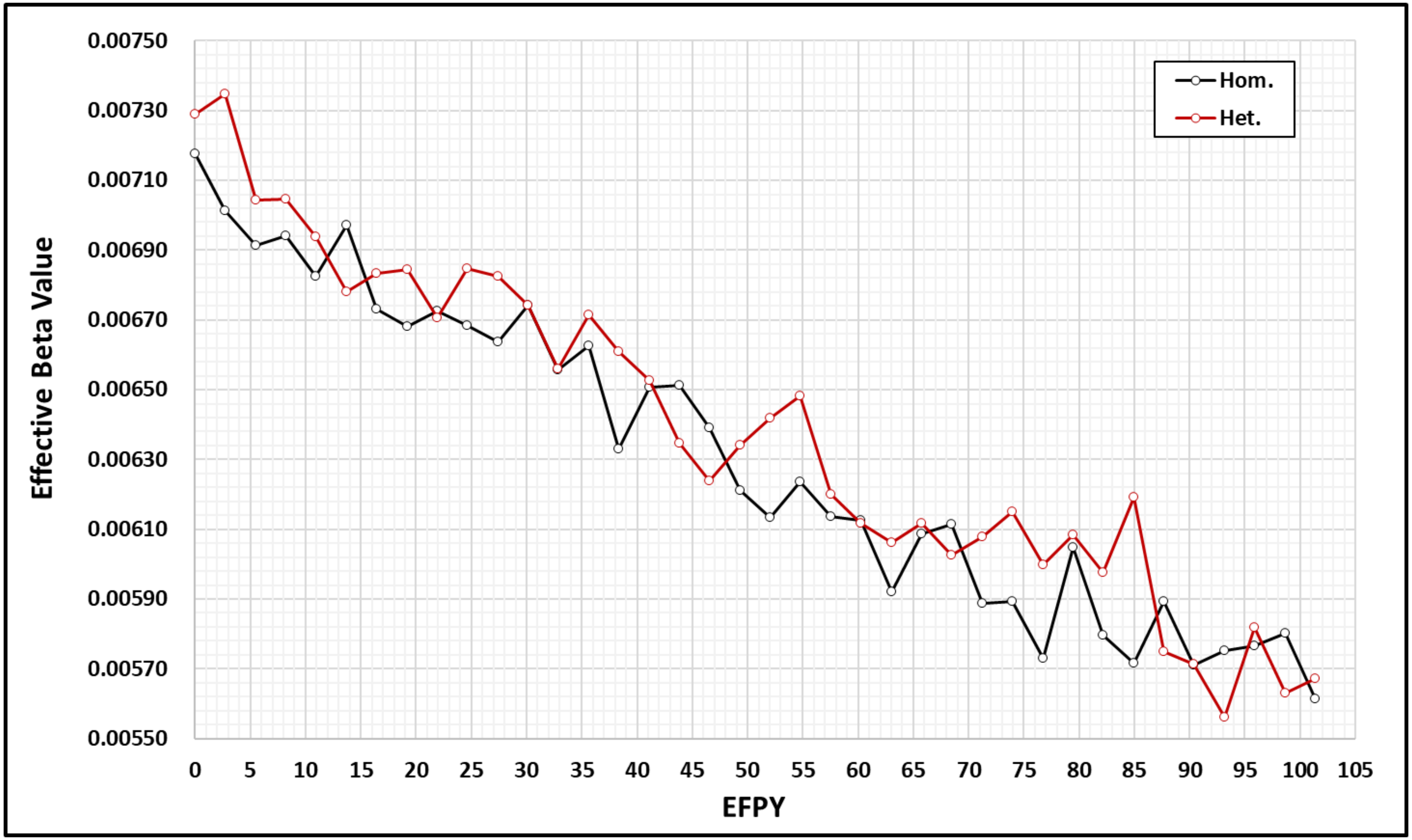
❖ Depletion results of multiplication factor and excess reactivity



- k-eff uncertainty: 40 pcm
- Hom. type : [~75 years / 33.45 GWd/tU (3.56 %burnup)], ~0.4 $ maximum excess reactivity
- Het. type: [~100 years / 50.31 GWd/tU (5.36 %burnup)], ~0.6 $ maximum excess reactivity

Numerical Results

❖ **Depletion results of multiplication factor and excess reactivity**



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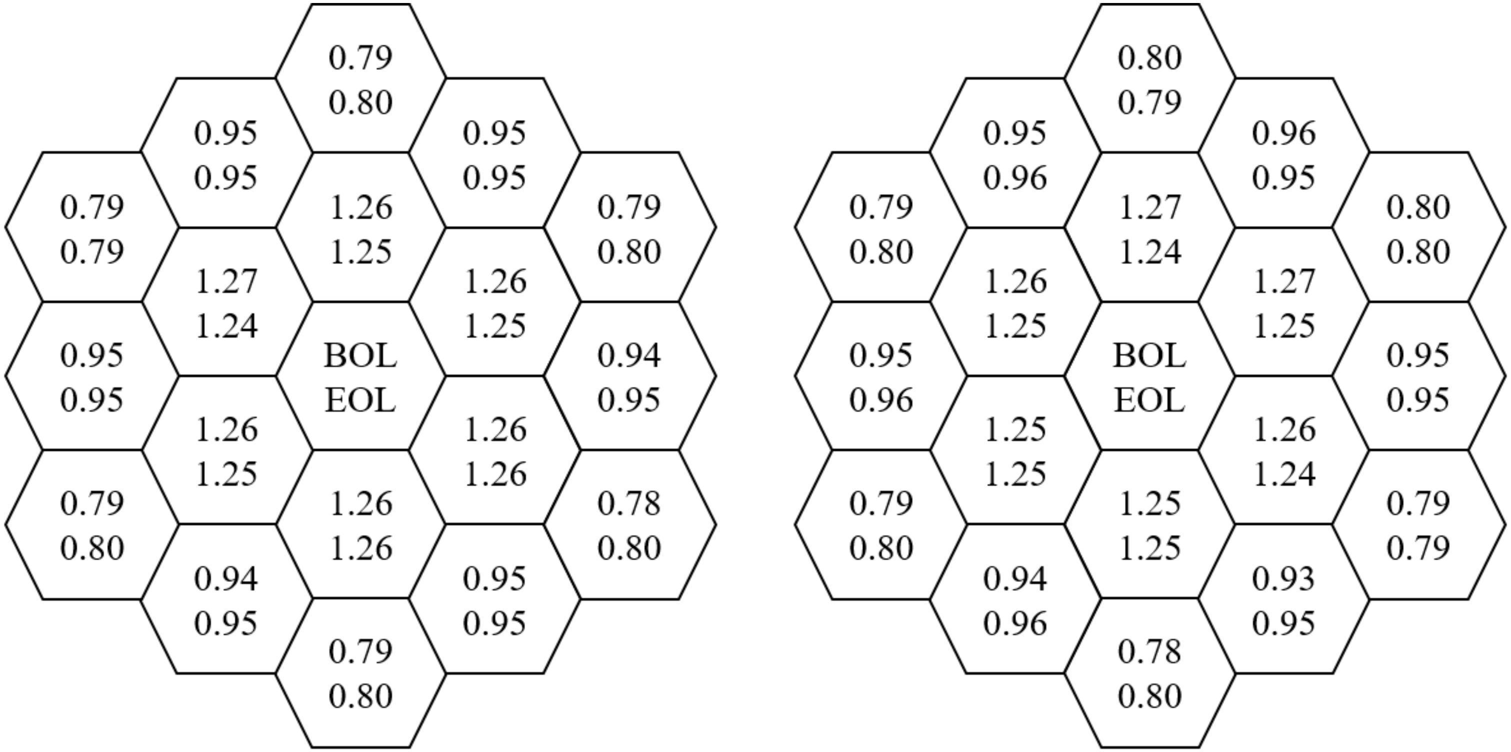
❖ Normalized radial power distribution

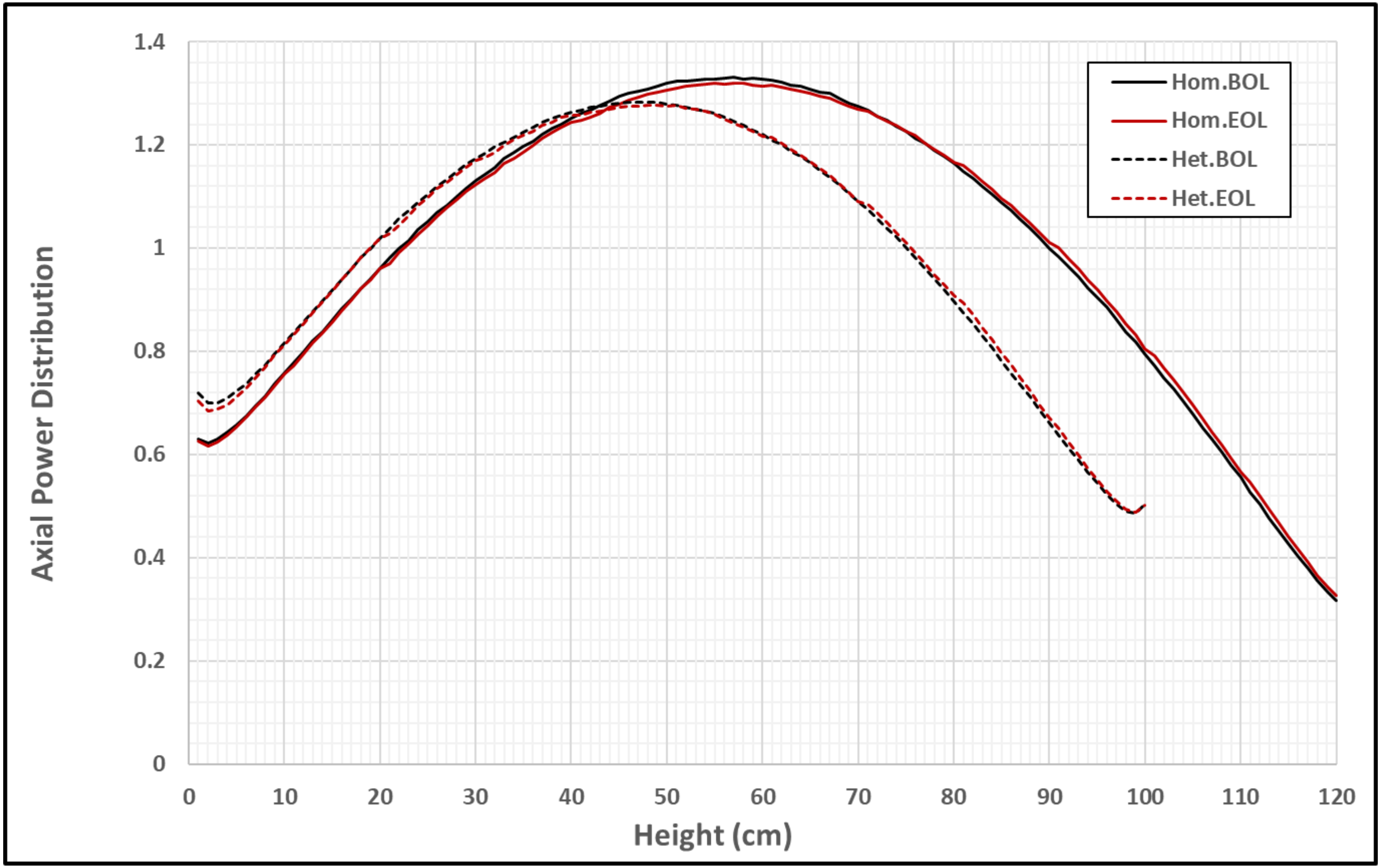


(a) Homogeneous Type (b) Heterogeneous Type

- Normalized power distribution at the active core depending on burnup.
- Using same fuel enrichment for all of FAs depending on type.
- Possibility of the different enrichment loading scheme depending on the position of FA to achieve flat radial power.

Numerical Results

❖ **Normalized axial power distribution**



Numerical Results

❖ **Reactivity feedback coefficients**

➢ Reactivity feedback coefficients depending on burnup

Model	Burnup	FTC (pcm/K)	CTC (pcm/K)	CVR (pcm)
Homogeneous Type	BOL	-0.742 ± 0.07	-0.002 ± 0.08	-43.49 ± 10.17
	EOL	-0.714 ± 0.07	-0.133 ± 0.09	16.30 ± 10.60
Heterogeneous Type	BOL	-0.649 ± 0.07	0.003 ± 0.08	-47.00 ± 10.10
	EOL	-0.569 ± 0.07	-0.006 ± 0.12	32.53 ± 10.66

- It is needed to obtain accurate reactivity coefficients due to large uncertainty especially for CTC and CVR.
- CTC values were calculated by perturbation of liquid and vapor sodium temperature.
- CVR values were obtained by assumption that all of liquid and vapor sodium are leaked.
- CVR was positive at EOL because the spectrum hardening effect by void would be dominant due to the accumulation of Pu.

Numerical Results

❖ Kinetic parameters

➢ Kinetic parameters of H-MMR

Energy group	BOL		EOL	
	Beta (β_i)	Lambda (λ_i)	Beta (β_i)	Lambda (λ_i)
		Homogeneous Type		
1st	2.01E-04 ± 0.0965	1.34E-02 ± 0.0006	1.68E-04 ± 0.1033	1.34E-02 ± 0.0006
2nd	1.10E-03 ± 0.0417	3.24E-02 ± 0.0006	9.57E-04 ± 0.0464	3.22E-02 ± 0.0009
3rd	1.22E-03 ± 0.0384	1.21E-01 ± 0.0003	9.31E-04 ± 0.0437	1.21E-01 ± 0.0008
4th	2.71E-03 ± 0.0265	3.10E-01 ± 0.0007	2.29E-03 ± 0.0293	3.10E-01 ± 0.0009
5th	1.35E-03 ± 0.0369	8.77E-01 ± 0.0010	1.09E-03 ± 0.0417	8.77E-01 ± 0.0011
6th	5.78E-04 ± 0.0547	2.95E+00 ± 0.0015	4.60E-04 ± 0.0651	2.94E+00 ± 0.0018
Effective	7.18E-03 ± 0.0161	5.50E-01 ± 0.0224	5.89E-03 ± 0.0179	5.41E-01 ± 0.0245
		Heterogeneous Type		
1st	2.06E-04 ± 0.0993	1.34E-02 ± 0.0006	1.42E-04 ± 0.1160	5.66E-01 ± 0.0248
2nd	1.11E-03 ± 0.0412	3.24E-02 ± 0.0006	9.57E-04 ± 0.0469	1.34E-02 ± 0.0009
3rd	1.11E-03 ± 0.0394	1.22E-01 ± 0.0003	8.61E-04 ± 0.0454	3.20E-02 ± 0.0009
4th	2.80E-03 ± 0.0259	3.10E-01 ± 0.0008	2.09E-03 ± 0.0311	1.21E-01 ± 0.0008
5th	1.46E-03 ± 0.0361	8.76E-01 ± 0.0010	1.16E-03 ± 0.0400	3.11E-01 ± 0.0009
6th	5.99E-04 ± 0.0564	2.94E+00 ± 0.0015	4.67E-04 ± 0.0678	8.80E-01 ± 0.0010
Effective	7.29E-03 ± 0.0158	5.70E-01 ± 0.0224	5.67E-03 ± 0.0185	2.94E+00 ± 0.0019

- The effective β_i was decreasing along with the burnup states due to the composition change of the fuel material, mainly Pu buildup.

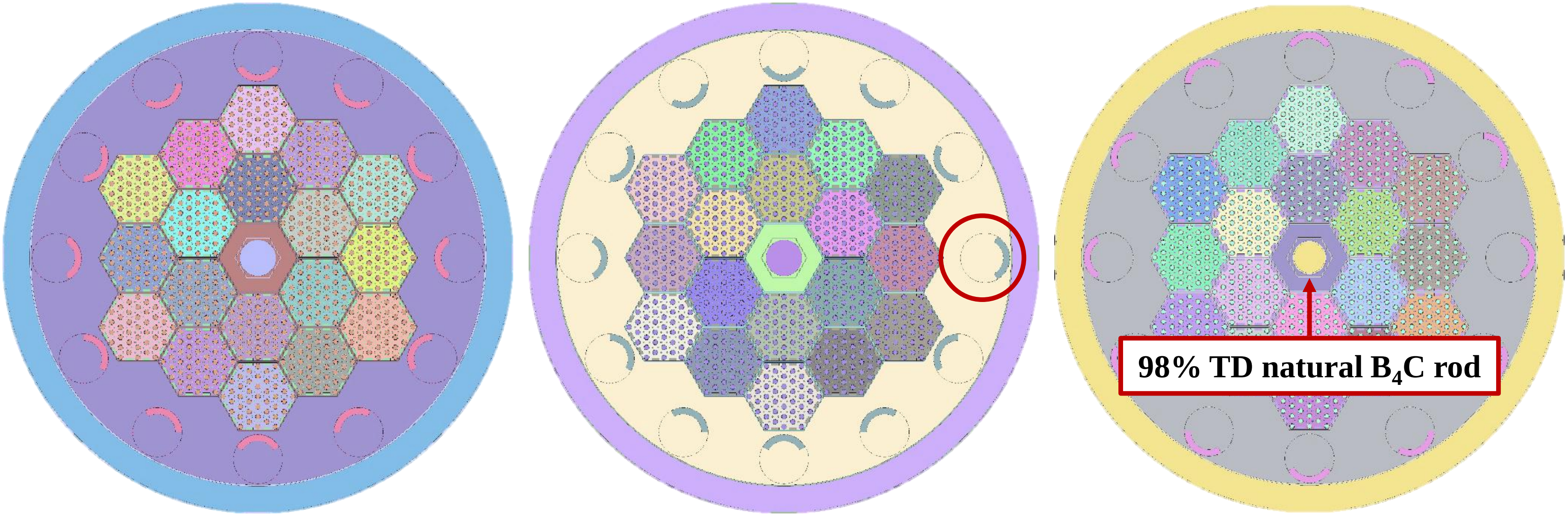
- All of kinetic parameters will be used for analyzing autonomous load-following by point kinetic model.

Numerical Results

❖ **Worth of the reactivity control system**

➢ Worth of the heterogeneous type H-MMR

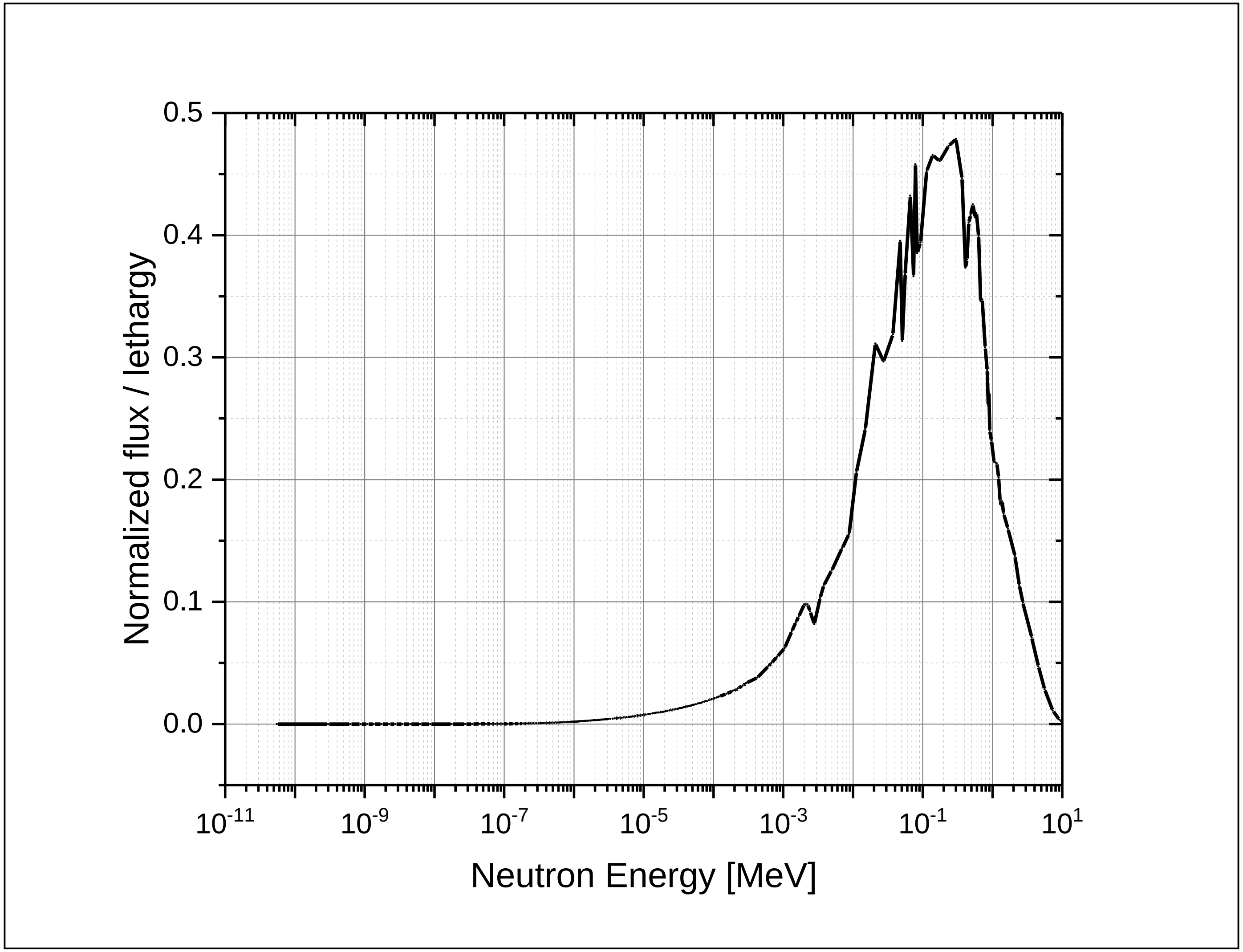
Worth	BOL (pcm)	EOL (pcm)
Primary	1822.67± 10.43	1571.11 ± 10.93
Primary-1	1690.65 ± 10.49	1441.83 ± 10.91
Secondary	2047.59 ± 10.53	1850.54 ± 10.96
Total	4167.12 ± 10.93	3784.79 ± 11.29



<Primary> **<Primary-1>** **<Secondary>**

❖ Neutron spectrum

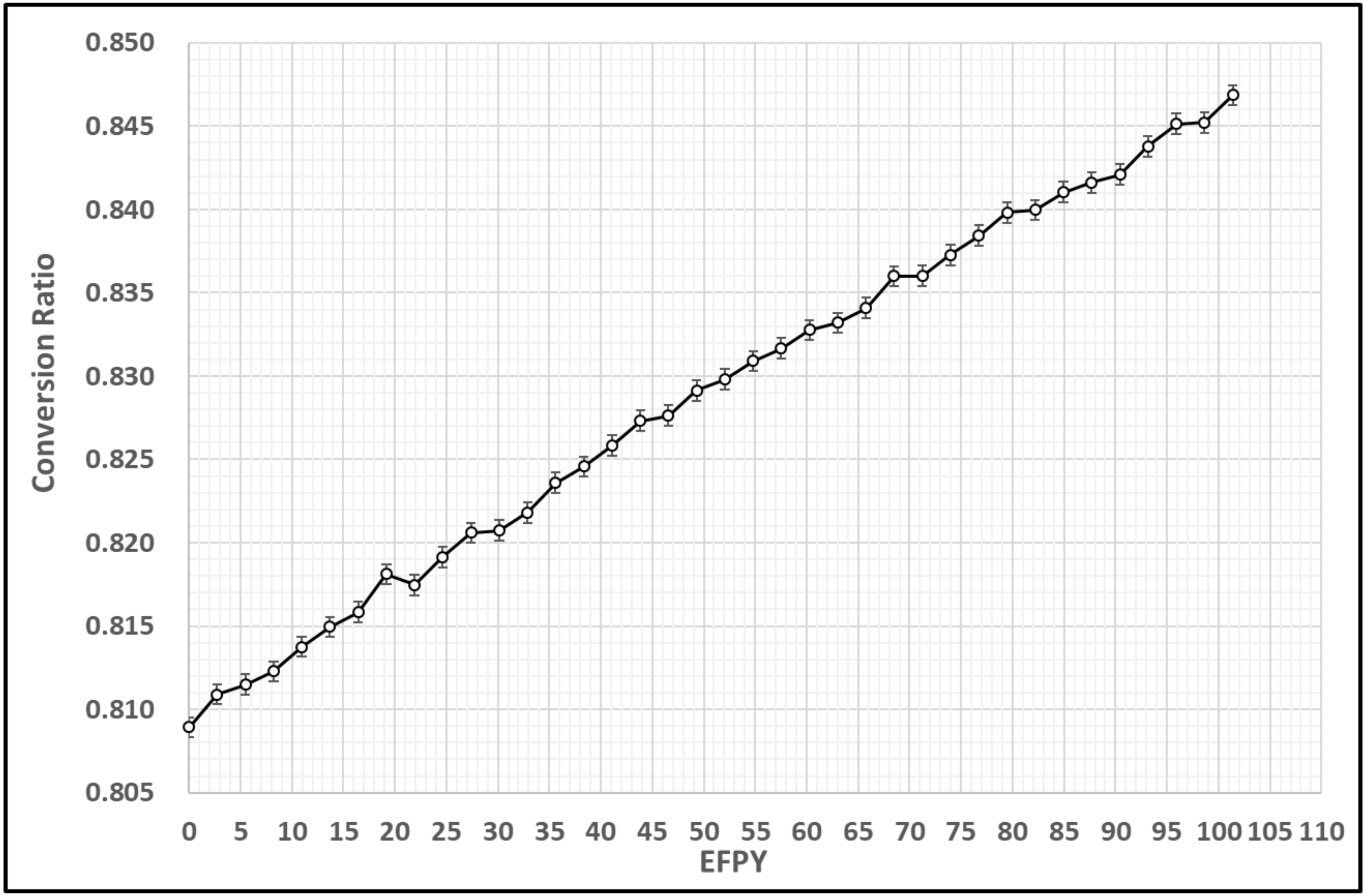
➢ Neutron spectrum of the heterogeneous type H-MMR



Numerical Results

❖ Conversion ratio

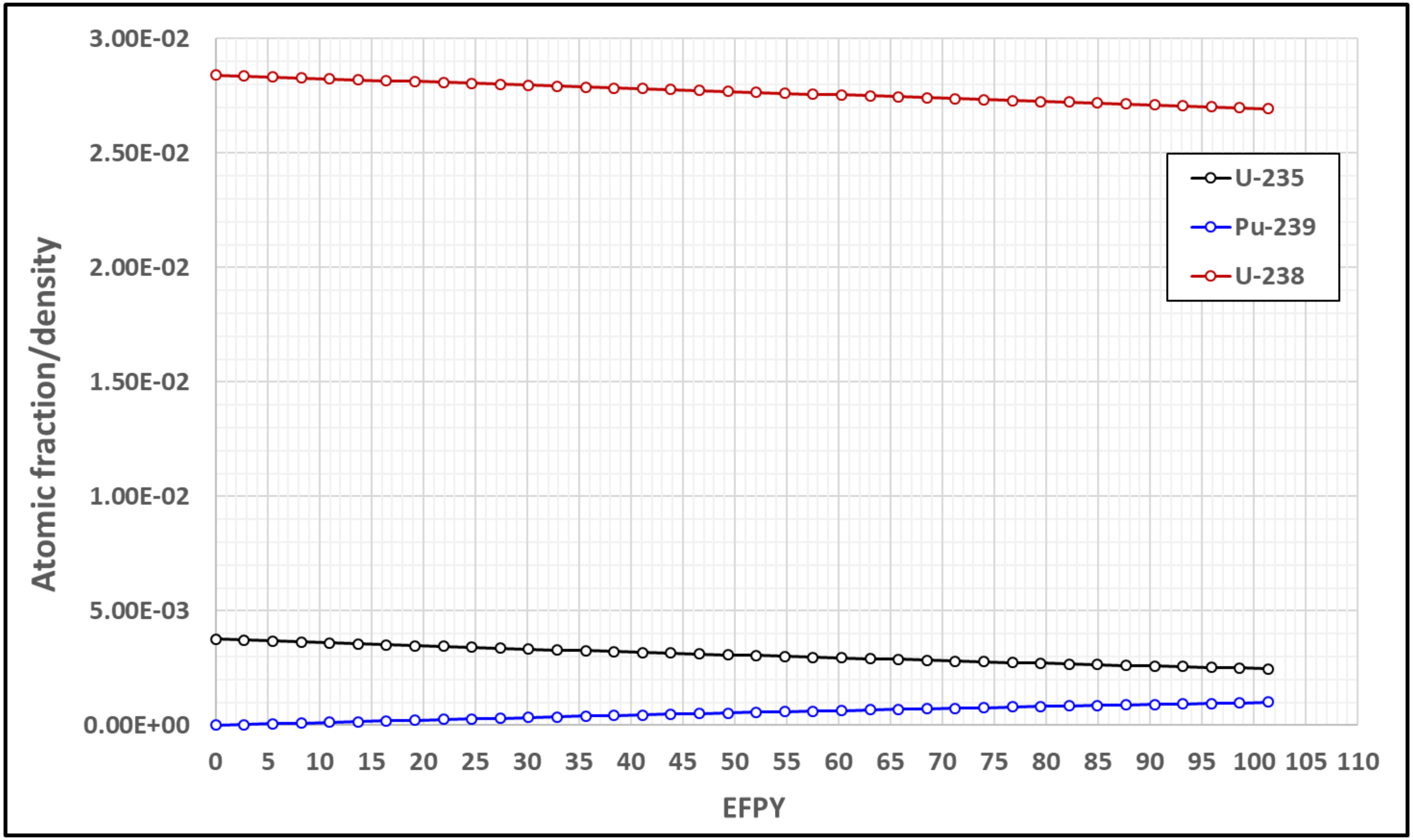
➢ Conversion ratio of the heterogeneous type H-MMR



Numerical Results

❖ Accumulation of Pu

➢ Accumulation of the Pu in heterogeneous type H-MMR



Conclusions and Future Works

❖ Conclusions

- The conceptual designs of the H-MMR has been proposed to achieve autonomous operation and ultra-long lifetime.
- H-MMR is loaded the inverted FA based on the $U^{15}N$ fuel with graphite moderator cooled by heat pipes.
- The concept of the ultra-long life H-MMR can be achievable mainly due to the features of the unique design of the inverted FA.

❖ Future Works

- Optimization H-MMR design in increased reactor power such as 18 or 24 MWth.
- Investigation on the feasibility of the autonomous operation with a point kinetics model.
- Specific heat transfer and transient analysis.
- Feasibility of manufacturing inverted $U^{15}N$ fuel inserted graphite moderator.

Thank you for your attention!