Core Nuclear Design of a Micro Modular High Temperature Gas-Cooled Reactor

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1. Introduction

Numerous studies have been conducted on the small modular reactors (SMR) in many countries around the world.[1-2] In particular, the micro modular reactors (MMR) are defined as reactors with an output power of 10MWe or less which was defined in "Safe and Secure Megawatt-Size Nuclear Power Workshop" hosted by ARPA-E(Advanced Research Projects Agency-Energy) of DOE at 2016. The features of MMR ensure inherent safety, non-proliferation, and enable in-factory certification. In addition, there should be no spent fuel pool on-site for nuclear security.

KAERI is developing the core concept of Micro modular High Temperature gas-cooled Reactor (MiHTR). The MiHTR is to deploy a remote site or island without electricity connection to supply the electricity and heat. In order to deploy a remote area, the concepts of MiHTR have introduced a long life (over 20 years) without refueling, no spent fuel storage on-site for security and non-proliferation, fully passive heat remove using reactor cavity cooling system (RCCS) at an accident condition for inherent safety.

This paper presents the concepts of fuel block and reactor core to achieve the long lifetime of a MiHTR. And, it describes the results of a core nuclear design and performance analysis of the MiHTR.

2. MiHTR Core Concept

2.1. Design Criteria

The thermal power of the MiHTR is 10MWth and it produces the 4MWe power using the gas-turbine Brayton cycle. The reactor core life time of a MiHTR should be longer than 20 year. Because the MiHTR is a high temperature gas-cooled reactor, TRISO fuel type is adopted and UO2 fuel is considered in the current design, and UN fuel can be used to extend the core lifetime. The helium is used as coolant. The core inlet/outlet temperature is 300/750℃, respectively. The outer diameter of reactor pressure vessel (RPV) is less than 3m to transport power production module to site by trailer or rail road.

The considerations of design criteria are as follows:

1) Maximum U235 enrichment: < 19.5w/o
2) Temperature coefficients: <0 %Δk/k/K
3) Shutdown margin: ≥1%Δk/k
4) Maximum fuel temperature: 1,250℃ at normal operation and 1,600℃ at accident conditions.

2.2. Design of Fuel Compact, Fuel Block, Reactor Core

2.2.1. Configuration of Fuel Compact and Block

In the MiHTR, the fully ceramic microencapsulated (FCM) fuel concept [3] in fuel compact is used in order to enhance an accident tolerance. Table 1 shows TRISO and fuel compact parameters. Figure 1 shows a fuel compact and unit cell geometry. The kernel diameter is 800μm and the diameter of TRISO particle including coating layers is 1,140μm. The fuel compact radius is 0.581cm and the radius of fuel compact hole is 0.649cm with graphite sleeve and gap. The 35% of TRISO packing fraction is used in this work.

The width of fuel block is 30cm and 0.2cm gap between block and block is considered as shown in Fig. 2. There are 108 fuel compact holes, 246 coolant holes, 6 burnable absorber compact holes and 6 graphite compact holes in a fuel block. The burnable absorber is used to minimize the excess reactivity. The 6 fuel compacts are replaced to graphite compacts in order to enhance neutron moderation which is located in inside of fuel block as shown in Fig. 2. In order to improve cooling performance of the MiHTR, the coolant hole is located in the corner of unit cell as shown in Fig. 1 and Fig. 2. We have named this a multi-cooling fuel block.[4] In this work, the radius of coolant hole is 0.4cm which was determined in consideration of manufacturability. From the results of the previous work in Reference 4, it noted that the maximum temperature of fuel compact of multi-cooling fuel block is much lower than that of GA-type fuel block in a thermal-fluid analysis using an unit cell model by CFX code.[4]

Figure 3 shows the configuration and geometry of a control rod block. The size of the control rod block is the same as the fuel block. The radius of control rod hole is 6.35cm and the thickness of absorber material is 1.5cm. The mixture of B4C and graphite is used as absorber material in this work. Also, Alloy 800H is used as clad material.

Table 1. TRISO and fuel compact specifications

TRISO	
Fuel type	UO_2
U-235 enrichment	Various
Kernel (diameter [μm])	800
Buffer layer (thickness [μm] / density [g/cm^3])	75/0.98
IPyC layer (thickness [μm] / density [g/cm^3])	35/1.85
SiC layer (thickness [μm] / density [g/cm^3])	40/3.2
OPyC layer (thickness [μm] / density [g/cm^3])	20/1.86
FCM Fuel Compact	
SiC Matrix Radius [cm]	0.581
SiC Matrix Height [cm]	5
SiC Matrix density [g/cm^3]	3.2
Packing fraction [%]	35

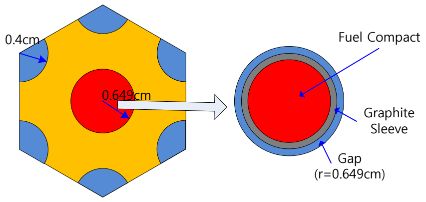


Fig. 1. Configuration of unit cell (imaginary) and fuel compact

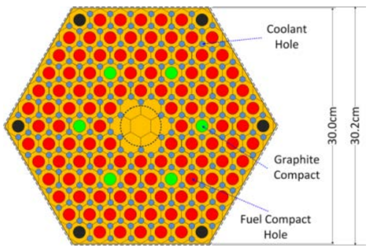
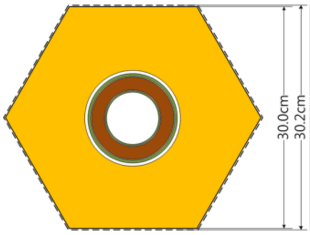


Fig. 2. Configuration of fuel block



	Radius(cm)	Thickness(cm)
CR hole	6.350	
CR outer clad OD	5.600	0.750
CR outer clad ID	5.400	0.200
CR absorber OD	5.350	0.050
CR absorber ID	3.850	1.500
CR inner clad OD	3.800	0.050
CR inner clad ID	3.600	0.200

Fig. 3. Configuration of control rod block

2.2.2. Configuration of Reactor Core

Figure 4 shows the configuration of MiHTR core. There are 24 fuel blocks and 7 control rod blocks per layer, respectively. The fueled core consists of axially 6 fuel layers. The height of fuel block is 79.3cm and height of top/bottom reflector is 120cm, respectively. The total core height for neutronics analysis is 715.8cm as shown in Fig. 4. The radius of outer side reflector is 138cm and the thickness of core barrel is 2cm. The thickness of coolant flow region is 5cm and the thickness of RPV is 5cm. Then, the outer diameter of RPV is 300cm which meets the design criteria of MiHTR.

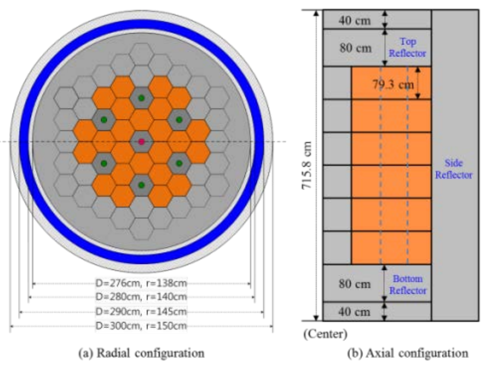


Fig. 4. Core design of MiHTR

2.3 Computational Tools

The core nuclear design and neutronics performance analysis of MiHTR core have performed by using the DeCART2D/CAPP code system. DeCART2D (Deterministic Core Analysis based on Ray Tracing for 2-Dimentional Core) [5-6] was developed by KAERI for two-dimensional lattice physics analysis. It is used to generate few-group homogenized cross section table sets required for a core diffusion analysis using multi-group cross section reduced from the ENDF/B-VII.1. CAPP (Core Analyzer for Pebble and Prismatic type VHTRs) [7] was developed by KAERI for three-dimensional diffusion analysis. It solves finite element diffusion equation for two- and three-dimensional geometry. Core burn-up analysis is performed using micro-depletion model with arbitrary nuclide chain. Thermo-fluid feedback can be simulated by a stand-alone model. Also, the CAPP code generates kinetics parameters for safety analysis.

3. Results of the Neutronics Performance Analysis

3.1. Results of Core Nuclear Design

The 1/6 2-D core model as shown in Fig. 5 is used to the generation of effective group constant data by using DeCART2D code in MiHTR core. Through numerous of sensitivity analysis, uranium enrichments and burnable poison (BP) contents are achieved to meet the design criteria as mentioned in Section 2.1. The BP compact consists of mixture of B4C and graphite. The control rods insert from the top of reactor core to make criticality of core. If the control rods inserted deeply, the power shape are skewed to bottom of core, then the maximum fuel temperature is increased. Accordingly, additional design criterion for control rod insertion depth is set to 30% in the work.

Enrichment zoning and burnable poison zoning are applied to MiHTR core design as shown in Table 2. In order to minimize the control rod insertion while satisfying design criterion for control rod insertion depth, the fuel layers are divided into upper and lower cores. When the control rod is inserted into the core, the axial power shape is skewed to lower part of the core. The radius of BP compact of lower core (fuel layer) is larger than that of upper core in order to alleviate the axial power increase of the lower core.

Table 2. Results of enrichment and BP zoning

2D Fuel Layer		Inner ring	Middle Ring	Outer Ring	BP Compact Radius
U235 Enrichment(w/o)		13.0	14.0	12.0/13.5/14.0	-
BP Content (%)	Lower Core	4.00	2.50	6.80	0.550 cm
	Upper Core	4.00	2.50	6.80	0.490 cm

And the BP compacts are replaced to graphite compact in Block A5 & A12 in order to flatten the radial power distribution as shown in Fig.5.

Based on the Table 2, Fig. 5 and 6, the core neutronics performance analysis was carried out. From the results of the performance analysis, the core lifetime of MiHTR reactor is achieved 7200EFPD which meets the core lifetime design criteria of more than 20years including 90% availability. Also, it is noted that the maximum control rod insertion depth is 20.50% and the maximum fuel temperature is 894℃ which was estimated using a stand-alone TF feedback module in the CAPP code.

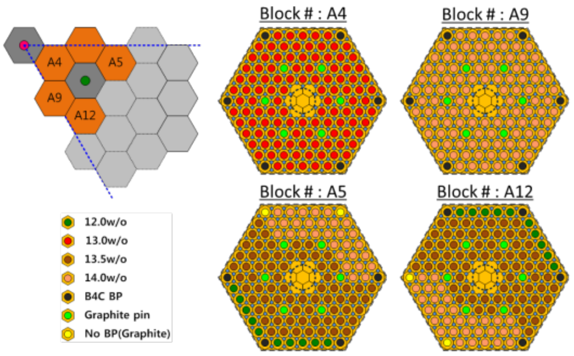


Fig. 5. 2D core model of core nuclear design

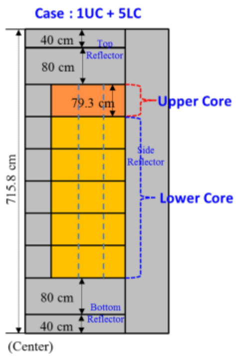


Fig. 6. 3D core model of core nuclear design

Figure 7 shows the k-effective changes without control rod movement during core lifetime. It is noted that the excess reactivity maintained less than 1,000pcm due to the optimized burnable poison design during core lifetime. Figure 8 shows the control rod insertion depth to make criticality of the MiHTR core. As you can see in the Fig. 8, the movement of control rod is only adjusted in the 1st fuel layer from top of the core.

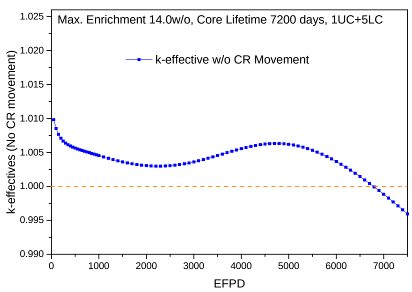


Fig. 7. k-effective changes without control rod movement

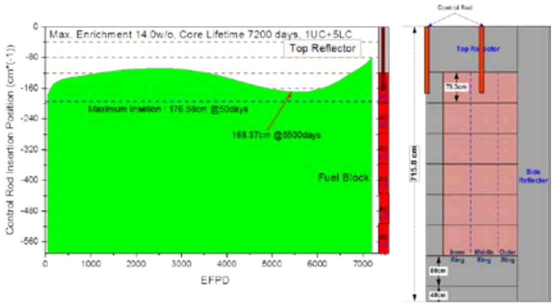


Fig. 8. Control rod insertion depth with burnup

Figure 9 shows the power axial offset (AO) during normal operation. The radial and axial power distributions of MiHTR core with burnup are show in Fig. 10. It is noted that the power sharing of upper core is larger than that of the bottom of the core. It results in the reduction of the maximum fuel temperature.

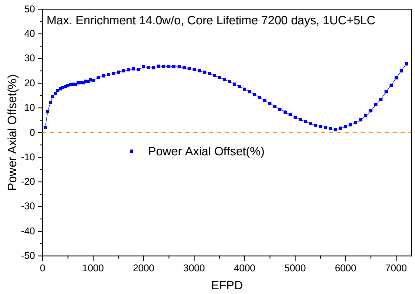
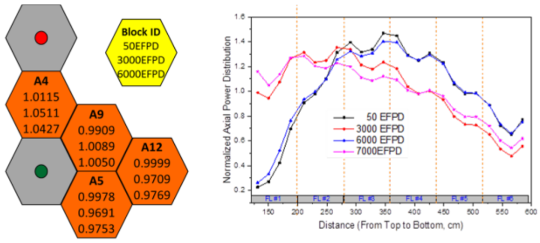


Fig. 9. Power axial offset with burnup



(a) Radial Power Distribution (b) Axial Power Distribution

Fig. 10. Power distributions with burnup

3.2. Temperature Coefficients and Shutdown Margin

Fuel temperature coefficients (FTC) (Doppler coefficients), moderator temperature coefficients (MTC) and isothermal temperature coefficients (ITC) are evaluated for several core burnup at full power operating conditions as shown in Figure 11. From the results, it is shown that the inherent temperature coefficients remain always negative over the core lifetime.

Table 3 shows the shutdown margin of the MiHTR core with burnup. It is conservatively assumed that 2 rods are not available for shutdown and cold state is at 20℃, while Xenon is assumed at equilibrium condition. Additional conservatism is taken into account by subtracting 20% of calculation uncertainty and additional 20% required by the safety analysis from the total reactivity inserted. From the results, it is found that the MiHTR core does meet the shutdown margin requirement of 1%Δk/k with sufficient margin.

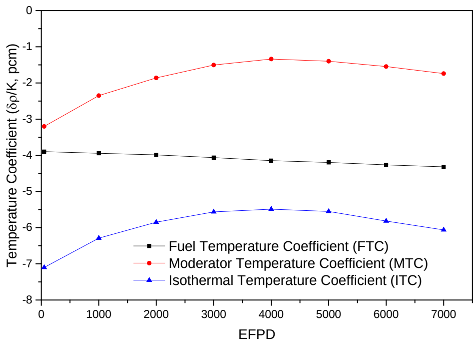


Fig. 11. Temperature coefficients with burnup

Table 3. Results of shutdown margin calculation

Conditions (@ 20℃)	EFPD			
	50	3000	5000	7000
Total shutdown Worth – 2 Control rods out	7.59	9.49	10.10	10.40
Uncertainty in calculation (20%)* +Safety analysis requirement (20%)**	-3.03	-3.79	-4.04	-4.16
Shutdown Margin (%Δk/k)	4.55	5.69	6.06	6.24

* Tentative until the uncertainty in calculation will be determined (Maximum 20% uncertainties from Fort Saint Vrain physics test)

** Tentative until the requirement by safety analysis will be determined.

4. Conclusions

This paper presented the core nuclear design of a micro modular high temperature gas-cooled reactor (MiHTR) which is developing by KAERI to deploy a remote area or island where power grid is unavailable. From the results of the core nuclear design analysis, the MiHTR reactor has achieved the core lifetime more than 20years which meets the design requirement. It is noted that the reactivity temperature coefficients are negative during core lifetime and the shutdown margin meets the shutdown margin requirement of 1%Δk/k.

Acknowledgments

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