Optimization design of a micro modular water-cooled reactor with a solid core

Hochul Lee[a], Hong Sik Lim[b], Tae Young Han[b], Hyun Chul Lee[a*]

[a]*Nuclear Engineering Division, School of Mechanical Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil geumjeong-gu, Busan 46241, Republic of Korea*

[b]*Korea Atomic Energy Research Institute, 989-111, Daedeok-daero, Yuseong-gu, Daejeon, 34057, Korea*

[*]*Corresponding author: hyunchul.lee@pusan.ac.kr*

1. Introduction

For inherently avoiding the severe accident caused by loss of coolant accident (LOCA) and improving the safety, a new micro-modular water-cooled reactor with a solid core was proposed [1]. The reactor uses SiC with high thermal conductivity for a moderator material and light water for a coolant and moderator material. It is operated with low power, ultra-long life, and boron free, and the accident tolerant control drum (ATCD) [2] is used as a reactivity control system. The reactor concept has the advantage of eliminating the severe accident by LOCA and not requiring an additional cooling system for removing the decay heat of the reactor after the shutdown [1].

In this paper, the optimization design was performed, and the thermal analysis was carried out using GAMMA + code [3]. The optimization design was performed using MCS [4], a Monte Carlo code developed by UNIST.

2. Design of Micro modular water-cooled reactor

Table I is a specification of the reactor. It is operated at 30MW$_{th}$ power for 30 years without replacing fuel until its end of life. The reactor consists of a total of 1,887 nuclear fuel blocks and a reflector consisting of a 50cm thick SiC is located around it. Nuclear fuel loaded into the reactor considered 20% enriched uranium to ensure enough reactor life. Figure 1 shows a cross-section of the reactor.

For an ultra-long life operation, the reactivity of the reactor was controlled using BP with gadolinium which has a very high neutron absorption cross-section. In this study, the BP was used as two forms, an IBA which is homogeneously mixed with uranium and a cylindrical BP type which is in the center of the fuel. The IBA type has the characteristics that the effect of the neutron absorption rapidly decreases after the beginning of life (BOL). On the contrary, the cylindrical BP type as shown in Figure 2 has the advantage that the poison effect of gadolinium keeps during the ultra-long life by the spatial self-shielding effect. IBA includes 4wt% and 8wt% gadolinium and cylindrical type has gadolinium oxide of a radius of 0.14cm, 0.18 cm, and 0.22 cm.

Table I. Specification for a micro modular water-cooled reactor with a solid core.

Parameters	Target Value
Reactor thermal power [MW$_{th}$]	30
Reactor life time [years]	30
Fuel material	UO_2
Burnable absorber material	Gd_2O_3
Fuel enrichment [%]	20
Number of fuel block [EA]	1887
Active fuel height [cm]	300.0
Effective core radius [cm]	71.3
Fuel radius [cm]	0.460
Coolant hole radius [cm]	0.619
Block width [cm]	3.100

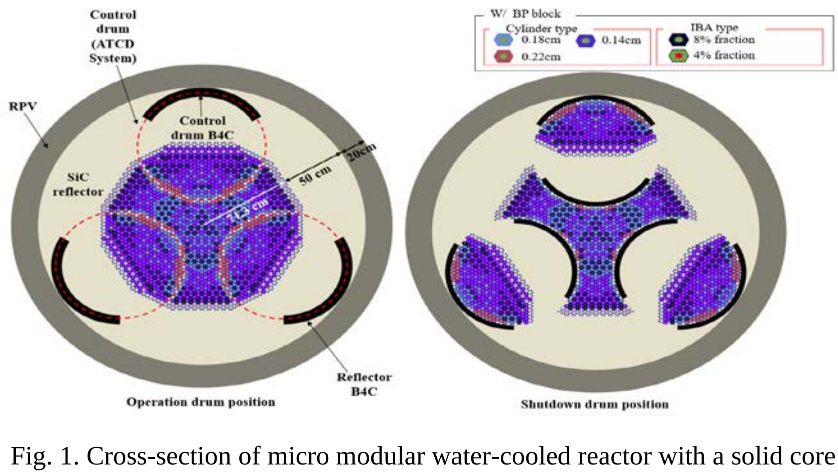

Fig. 1. Cross-section of micro modular water-cooled reactor with a solid core

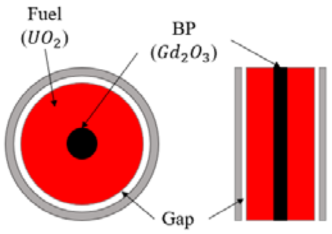

Fig. 2. Cross-section of nuclear fuel containing gadolinium in the form of a cylinder.

The reactor has two independent shutdown system. The first is ATCD used during normal operation and, the secondary is a coolant drain system when reactivity control is not possible due to the malfunction of the ATCD. Unlike conventional control drum, ATCD consist of the neutron absorption material, reflector material, and nuclear fuel. ATCD is positioned to maintain the criticality(k_{eff}=1.0) of the reactor when the reactor is operating at full power.

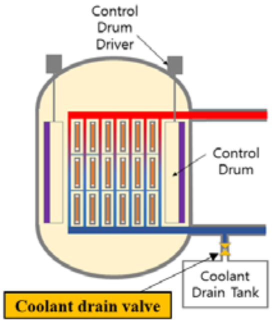

Fig. 3. The coolant drains system of a micro modular water-cooled reactor with a solid core

Figure 3 shows the coolant drain system. The coolant drain system automatically discharges the coolant into the drain tank by opening the valve when the reactor cannot be stopped due to the malfunction of the ATCD. Since the drain tank maintains a vacuum, the coolant is discharged to the drain tank within a few seconds due to the pressure difference from the reactor.

3. Neutronics analysis for the micro modular water-cooled reactor

Neutronics analysis was performed with MCS code developed by UNIST, and an ENDF/B-VII.0 continuous nuclear cross-section library was used. The standard deviation of all MC calculation results is 20 pcm or less. The core temperature assumed 900K, and the coolant temperature assumed 600K.

3.1 Depletion Calculation

The depletion calculation for the reactor was performed with the condition of the operation of 30 years and the thermal power of 30 MW. All control drums were at the operation drum position as shown in the left side of Figure 1. Figure 4 shows the multiplication factor as a function of the effective full power day (EFPD). The multiplication factor is 1.02876 at the beginning of the life and 1.00055 after depletion of 30 years, respectively. It reveals that the proposed reactor can be operated at 30 MWth for 30 years without a fuel reload. Also, the figure presents that the reactivity reduced by the BP is 46113 pcm at the beginning of the life and 7431 pcm at the end of life, respectively. These results reduced the gadolinium residual effect of the previously designed core by 3.6 times [1].

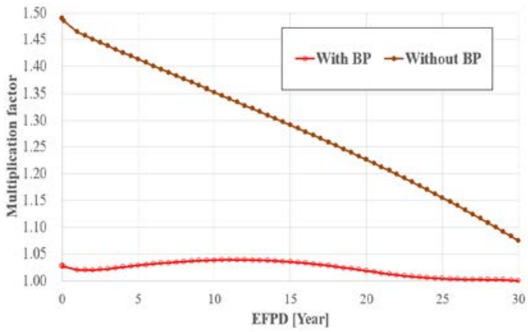

Fig. 4. The result of the depletion calculation.

3.2 Shutdown system evaluation

In this section, the shutdown margin evaluation of the control drum was performed by comparing the multiplication factor at the operation and shutdown position of the control drum. The coolant temperatures for the calculation were 600 K at the hot full power and 300 K at the cold zero power, respectively. Table II shows the multiplication factors depending on the position of the control drum and the coolant temperature. When the control drum is in the shutdown position, the multiplication factor is less than 0.85 for the reactor lifetime. Even though it is shut down and then cooled for enough time, the multiplication factor of the reactor is less than 0.95,. It is clear that the control drum has an enough shutdown margin for stopping the reactor.

Table II. The multiplication factor depending on the control drum position and coolant temperature.

Drum position	Operation position [600K]	Shutdown position [600K]	Shutdown position [300K]
BOL (0year)	1.02876	0.84109	0.94000
MOL1 (11year)	1.03969	0.84131	0.94275
MOL2 (15year)	1.03579	0.83950	0.94261
EOL (30year)	1.00055	0.79266	0.88733

* The standard deviation of all calculations is 20 pcm or less

Table III shows the multiplication factors when all coolant in the reactor is discharged to the drain tank at four points of the reactor life. At this time, all control drums are in the operation drum position. From the results, it is clear that the secondary shutdown system has a good performance to shut down the reactor without the control drum system.

.

Table III. The multiplication factor when all coolant is discharged into the drain tank.

	Drain of coolant	Std. [pcm]
BOL (0year)	0.77889	10
MOL1 (11year)	0.71007	11
MOL2 (15year)	0.67935	10
EOL (30year)	0.53154	13

3.3 Reactor accident scenarios

The reactor is assembled at the factory and then transported to the site via land and sea. If the reactor is flooded with rivers, lakes, or seas due to an accident during transportation, it is essential to keep the core subcritical. In addition, even if the control drum is separated from the core by external shock and water enters the empty space, the reactor must always maintain a sub-critical condition. The reason is that water can cause a criticality of the core as a good moderator. Figure 5 shows the four scenarios for reactivity accident during reactor transport. For all scenarios, the control drum was at the shutdown position in transit. Case 1 is a situation that the reactor was flooded without missing the control drum. Case 2-4 are situations that the reactor was flooded with missing the control drum. In each case, one, two, and three control drums were lost, and the empty space was filled with room temperature water.

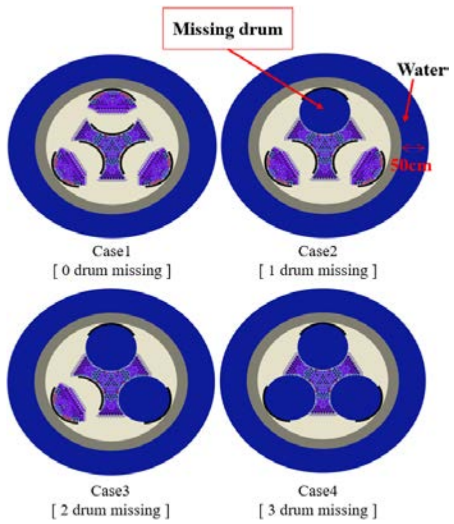

Fig. 5. Reactor flooding scenario during transportation.

Table IV shows the multiplication factors depending on the flooding scenario. The multiplication factor has the largest value of 0.93929 when only the reactor is flooded without missing the control drum, and the value of the other cases are less than that of the case 1.

Table IV. The result of reactor flooding scenario

Accident scenario	Multiplication factor	Std. [pcm]
Case1	0.93929	25
Case2	0.93657	17
Case3	0.93156	18
Case4	0.88581	19

4. Evaluation of core cooling performance.

The thermal analysis of the reactor was performed using GAMMA + code. Figure 6 show the GAMMA+ calculation model for the reactor coolant system within the reactor vessel and the reactor cavity cooling system. The core barrel was not considered when performing the nuclear design, but a 3 cm core barrel was considered when performing the thermal analysis. The reactor was subdivided into 6 radial directions and 10 axial directions for calculation accuracy. The six subdivided radial cores accommodate 52,157,262,367,472 and 577 nuclear fuel rods, respectively.

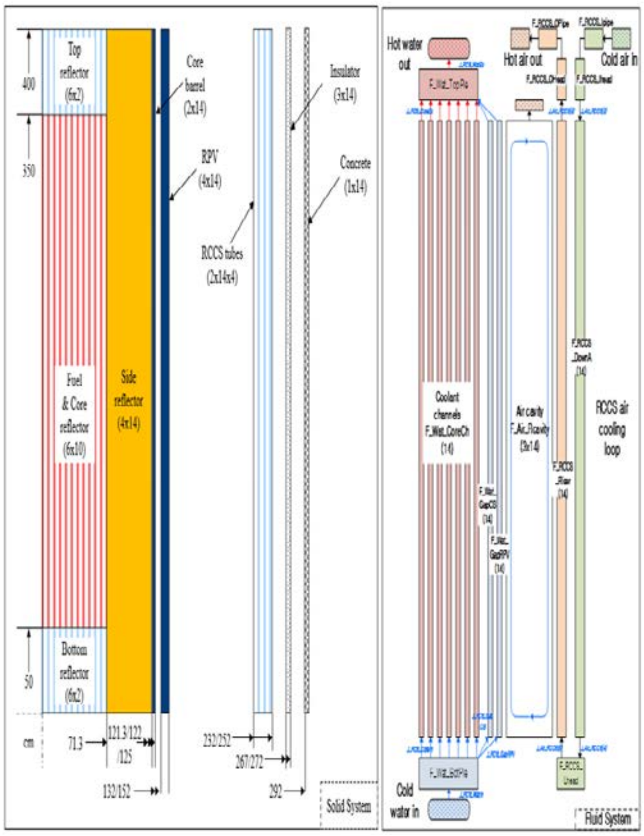

Fig. 6. Solid and fluid system axial cross-sections of the GAMMA + calculation model

The core thermal analysis was performed assuming steady-sate and LOCA**.** Thermal analysis of steady-state was performed assuming a emissivity of 0.8. When the emissivity is 0.8, the maximum fuel temperature is 847.7℃ and the RPV temperature is 316℃. The heat loss by natural convection is 112.65 kW (0.37%). Table V shows the results of the thermal analysis depending on the emissivity at steady-state.

Table V. Result of thermal analysis at a steady state.

Emissivity	Elements	Values
0.8	Max. fuel temp [℃]	847.7
	Max. core temp [℃]	339
	Max. RPV temp [℃]	316
	Max. RCCS tube temp [℃]	181
	Max. concrete temp [℃]	51
	RCCS air flow [kg/s]	1.68
	Heat loss by air [kw]	112.65 (0.37%)

The following three assumptions are applied to the core heatup analysis.

- Coolant pressure decreases linearly from 15.5 MPa to 0.1 MPa in 10 sec.
- Coolant mass flow decreases linearly from 162 kg/s to 0 kg/s in 10 sec.
- Core power shifts to decay heat with 1 sec delay.

Figure 7 shows the nuclear fuel and RPV temperature in a LOCA. When the emissivity is 0.8, nuclear fuel increases to 1420℃ in 80 hours and then decreases to 1000℃ over time. The temperature of RPV increases to 343℃ for 120 hours and then decreases.

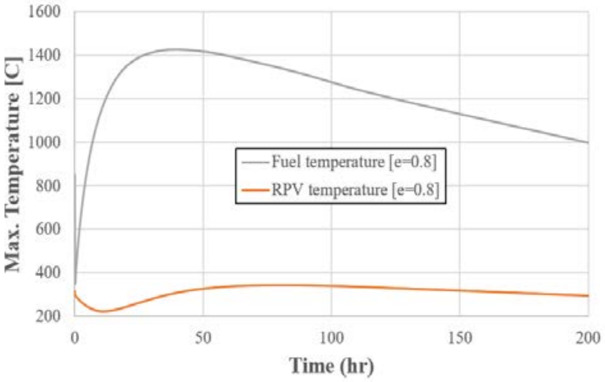

Fig. 7. Nuclear fuel(left) and RPV (right) temperature in a LOCA

5. Conclusions

The optimization design of micro modular water-cooled reactor with a solid core was carried out based on previous design. A neutronic feasibility study was carried out using MCS code. Core neutronics analyses showed major advantage characteristics. Ultra long-life core can be achieved by using Gadolinium burnable poison as two types of forms. Result of depletion calculations present that the residual effect of gadolinium is 7431 pcm.

A new type of control drums, Accident Tolerant Control Drum (ATCD), helps to have large shutdown margins: less than 0.85 at hot shutdown state of 600 K, and less than 0.95 even at cold shutdown state of 300 K.

Thermal analyses for full power steady condition showed relatively high maximum fuel temperature of 847.7℃. Core heatup analysis was performed at the worst condition where the reactor shutdown is done by coolant drain not control drums' rotation and thus decay heat source remains to be concentrated at the core center. The maximum RPV temperature is 316℃ at about 120 hours and much low even below the operating limit of 371℃. Therefore there is no safety concern on fuel and RPV integrity.

This reactor concept eliminates reactor melting accidents caused by LOCA. And it is expected to improve the inherent safety of small modular reactors that use light water as a coolant.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (2017M2B2A9A02049804).

REFERENCES

[1] H. Lee., S. G. Kang., H. C. Lee., A Concept of Small Modular Water-cooled Reactor with Solid Core, The 6th International Conference on Nuclear and Renewable Energy Resources (NURER2018), Sep. 30~03 Oct, 2018, Jeju, Korea.
[2] H. C. Lee, T. Y. Han, H. S. Lim, and J. M. Noh, An accident-tolerant control drum system for a small space reactor, Ann. Nucl. Eng.,79, pp.143-151, 2015.
[3] H. S. Lim., GAMMA+1.0 Volume I: User's Manual, KAERI/TR-6167, Korea, 2015.
[4] H. Lee., Development of a New Monte Carlo Code for High-Fidelity Power Reactor Analysis, Ph. D. Thesis, UNIST, 2019.