Conceptual Core Design and Preliminary Neutronics Analysis for a Space Heat Pipe Reactor

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1. Introduction

National Aeronautics and Space Administration (NASA) has been developing a small space nuclear reactor, Kilopower, for supplying power in space, and the ground demonstration named KRUSTY (Kilopower Reactor Using Stirling TechnologY) has been successfully completed [1]. A few years ago, Korea Atomic Energy Research Institute (KAERI) studied mass reduction and safety enhancement during launch accidents of a low-enrichment uranium-fueled space reactor [2, 3].

In this paper, conceptual designs of a space heat pipe reactor (HPR) that can be mounted on a Korean launch vehicle were made based on KAERI's previous works. The concept of an accident-tolerant control drum, which was considered in a previous study, was applied in this work, and a neutronic feasibility study was performed according to various accident scenarios using the Monte Carlo code, McCARD [4].

2. The space heat pipe reactor (HPR) core overview

The space HPR core concept currently under development is designed to the following requirements:

- Life time: > 15 years
- Operating temperature: 700-750℃
- Thermal power: 5-10 kW_{th}
- U-235 enrichment: < 20.0w/o
- Total reactor mass*: < 1.2 ton
- Reactor size*: < 1.2m (diameter) x 3m (height)

*The values for the entire reactor system

Figure 1 shows the radial cross-sections of the space HPR core. The core consists of 72 fuel rods, 7 heat pipes, 6 control rods, a hexagonal prism shape moderator, and a cylindrical reflector. The space HPR core uses UO_2 fuel with U-235 enrichment of 19.5w/o, a B_4C absorber with B-10 enrichment of 90.0w/o, a $ZrH_{1.5}$ moderator, and a BeO reflector, which were considered in previous work [2, 3]. The heat pipe will use Na or NaK, and the detailed design will be made in a later study. The diameter and active core height of the core are 53 cm and 25 cm, respectively.

In this core, the accident-tolerant control drums which include not only 1 control rod but also 7 fuel rods are installed at the interface between the moderator and the reflector. As shown in Fig. 1(b), when the control drums are located at the shutdown position, some fuel rods are moved to a position far from the core and the absorbers are inserted deeper than a conventional control drum that does not include fuel material, resulting in high negative reactivity [3].

3. Neutronics analysis for the space HPR

All calculations were performed using McCARD with continuous energy cross section libraries from ENDF/B-VII.1 [5]. The MC eigenvalue calculations are based on 1,000 active cycles with 100,000 histories per cycle, which made all standard deviations smaller than 10 pcm. The temperatures are assumed to be 1020 K (747 ℃) in operation and 300 K for shutdown or accident cases.

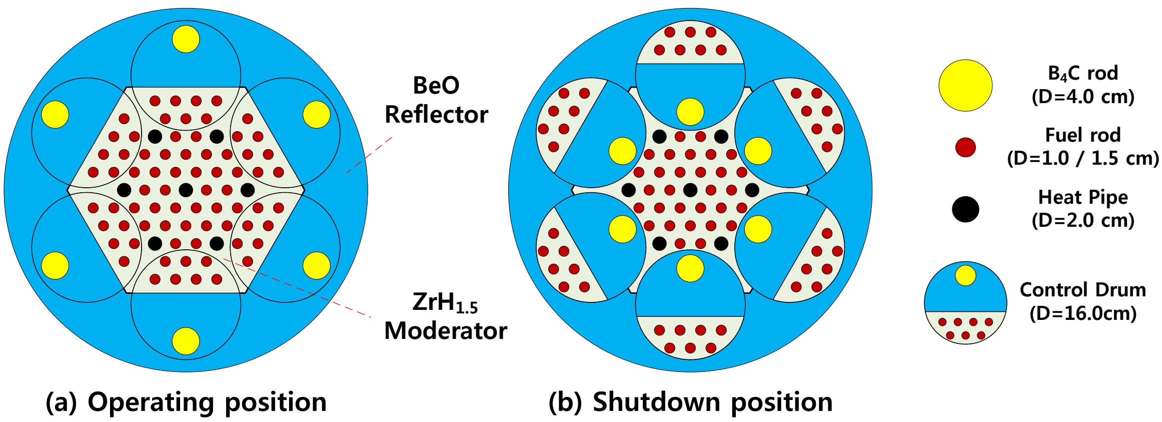

Fig. 1. The radial cross-sections of the space heat pipe reactor (HPR)

3.1 Numerical Results by Angle of the Control Drum

Table I and Fig. 2 show the results of k_{eff} for each angle when one or all of the control drums are rotated. These results show that the reactor can be shutdown with only one control drum, and this core has sufficient shutdown margin when all control drums are used.

Figure 3 shows the results of fission power distribution by angle of the six control drums. The pin power peaking factor 1.51 at 0 degree and 1.91 at 30 degree. This value is lowered to 1.35 at 0 degree if the diameter of the fuel rod is 1.5 cm instead of 1.0 cm.

Table I: The results of k_{eff} by angle of the control drums

Angle [degree]	k_{eff} 1 CD rotation	k_{eff} all CDs rotation
0 (operation)	1.02863	1.02863
15	1.02789	1.02429
30	1.02624	1.01319
45	1.02443	0.99685
60	1.02127	0.97369
75	1.01723	0.93939
90	1.01219	0.89629
105	1.00642	0.85145
120	1.00015	0.80854
135	0.99408	0.76594
150	0.98819	0.72451
165	0.98432	0.69299
180 (shutdown)	0.98294	0.68109

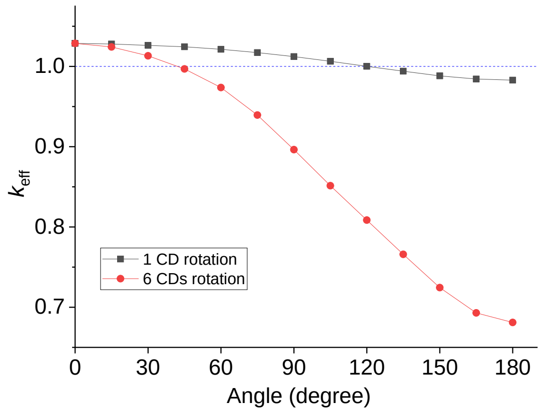

Fig. 2. The results of k_{eff} by angle of the control drums

3.2 Depletion Calculation

The burnup calculations are performed at the power level of 10 kW_{th}. All control drums are located in the operating position, as shown in Fig. 1(a). The depletions proceeded only for the fuel rods and the control rods.

The calculated values of k_{eff} are 1.02863 for the beginning of the cycle and 1.01172 after 5,800 EFPD of depletion. As shown in Fig. 4, the proposed core design can be operated for more than 15 years at the power level of 10 kW_{th}.

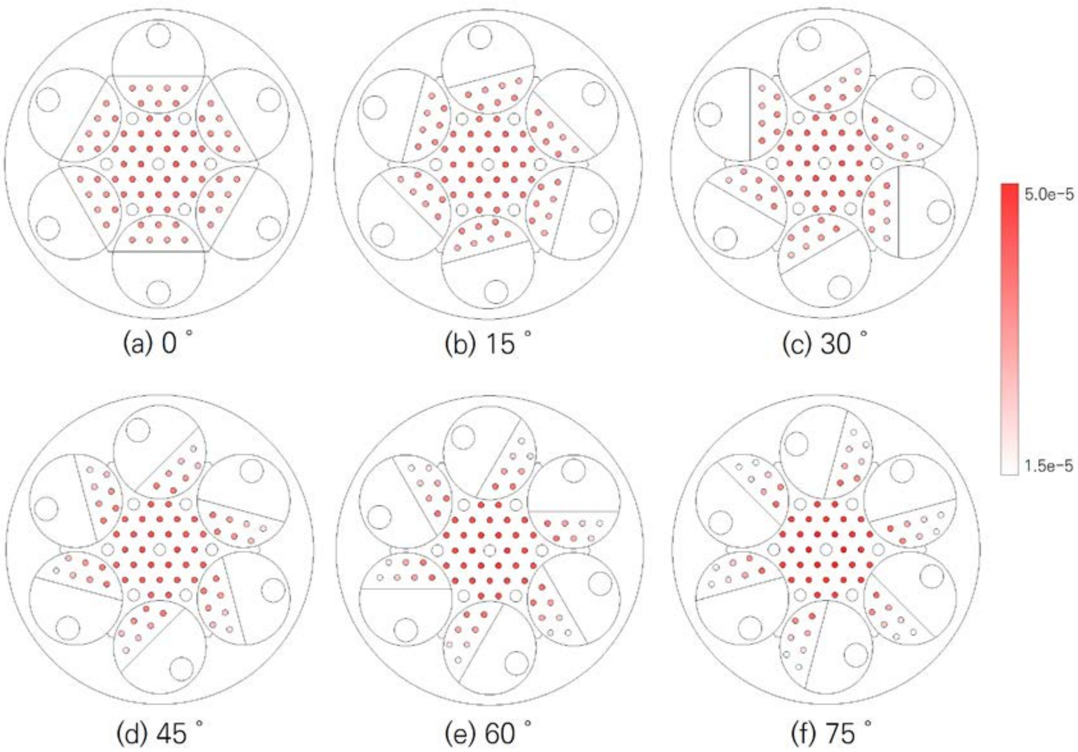

Fig. 3. The results of fission power density [MW_{th}/cm^3] distribution by angle of the control drums

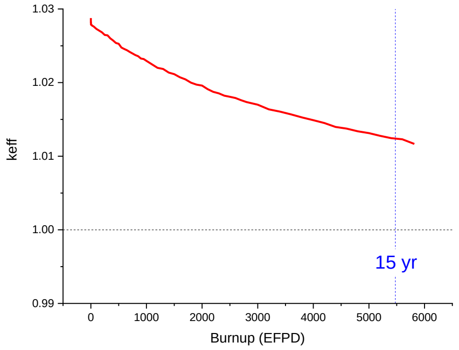

Fig. 4. The k_{eff} results of depletion calculations

3.3 Launch Failure Accident Scenarios

If the launch fails and the reactor falls to the ground, the reactor must remain in a subcritical state. Because water shows good performance as a moderator and a reflector for a thermal reactor, calculations for launch failure accident scenarios are made for the case in which the reactor falls into fresh water after the launch failure. Calculations are performed for all cases in which 1~6 control drums are separated from the reactor, as shown in Fig. 5.

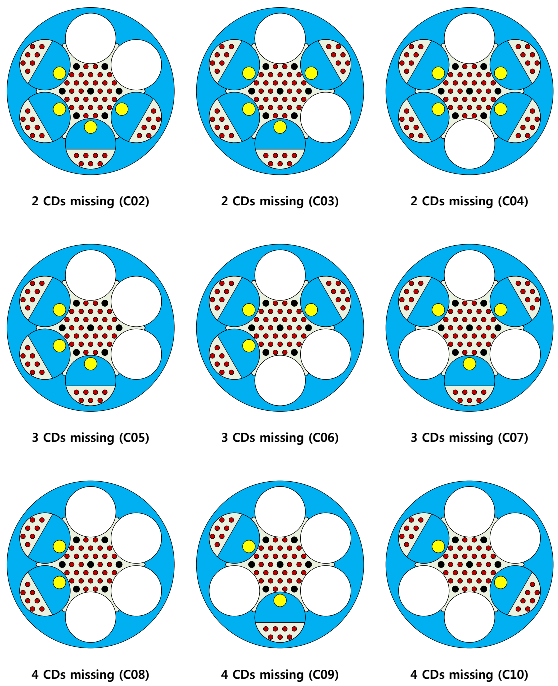

Fig. 5. The positions of the missing control drums

As shown in Table II, the k_{eff} values are less than 1.0 and the reactor core maintains the subcritical state in all cases except when the reactor is not broken and all control drums are rotated to the operating position. The probability of all control drums rotating to the correct operating position with the reactor intact is in fact extremely low, so the proposed reactor is safe in launch failure accident scenarios.

Table II. The k_{eff} results of the launch failure accident scenarios

No.	Scenarios	CDs Position	
		Shutdown	Operation
C00	As launched	0.69594	1.03100
C01	1 CD missing	0.70248	0.98534
C02	2 CDs missing	0.71136	0.95305
C03	2 CDs missing	0.70927	0.93877
C04	2 CDs missing	0.70904	0.93386
C05	3 CDs missing	0.71998	0.91544
C06	3 CDs missing	0.71789	0.89459
C07	3 CDs missing	0.71587	0.87940
C08	4 CDs missing	0.72845	0.86599
C09	4 CDs missing	0.72661	0.84385
C10	4 CDs missing	0.72655	0.84059
C11	5 CDs missing	0.73681	0.80174
C12	6 CDs missing	0.74652	0.74652

4. Conclusion

The conceptual design of a space heat pipe reactor (HPR) was carried out based on previous work at KAERI. The concept of an accident-tolerant control drum was applied in this space HPR and a neutronic feasibility study was performed according to various accident scenarios using McCARD.

From the results of the neutronic feasibility study, it is shown that the designed space HPR concept can be operated and shut down by rotating the control drums, and can be operated for more than 15 years with a power level of 10 kW_{th}. This reactor core also remains in a subcritical state when it sinks in water with 1~6 control drums missing, so the designed reactor is safe in launch failure accident scenarios.

ACKNOWLEDGMENTS

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REFERENCES

[1] D. Poston, M. Gibson, P. McClure, T. Godfroy, and R. Sanchez, Results of the KRUSTY nuclear system test, Nuclear and Emerging Technologies for Space (NETS-2019), Feb.25-28, 2019, Richland, WA.
[2] H. C. Lee, H. S. Lim, T. Y. Han, and S. Cerba, A neutronics feasibility study on a small LEU fueled reactor for space applications, Ann. Nucl. Eng., 77, pp. 35-46, 2015.
[3] 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.
[4] H. J. Shim, B. S. Han, J. S. Jung, H. J. Park, and C. H. Kim, McCARD: Monte Carlo code for advanced reactor

design and analysis, Nucl. Eng. Technol., Vol. 44, No. 2, pp. 161-176, 2012.
[5] M. B. Chadwick, et al., ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data, Nucl. Data Sheets, Vol. 112, pp. 2887-2996, 2011.