

Conceptual Design and Neutronics Analysis of a 30 kWth Monolithic Heat Pipe Reactor (SIREUS) for Space Applications

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1. Introduction

Heat Pipe Reactor (HPR) is innovative micro reactors that utilize the phase change and capillary action of encapsulated liquid metals to transport core heat. This mechanism enables entirely passive heat removal without the reliance on gravity and mechanical pumps. By simplifying external cooling systems such as pumps, piping, and condensers, HPR minimize potential failure points while offering superior advantages in miniaturization and mass reduction. These attributes make it a premier candidate for space applications where high reliability is important under stringent mass, volume, and power constraints.

As long-duration missions to the Moon and Mars expand, the demand for resilient and long-life power sources is intensifying because traditional solar and battery systems reach their operational limits. Consequently, global research into space-rated micro reactors is accelerating, as evidenced by the U.S. KILOPOWER/KRUSTY and China's HPCR projects. In alignment with these global trends, domestic efforts are also underway to bolster capabilities and establish a strategic foundation for securing space nuclear power and propulsion technologies [1~2].

This study presents a conceptual design of a 30 kWth monolithic HPR tailored for space-based power supply. The monolithic architecture provides inherent safety advantages including robust negative reactivity feedback, low power density, extended core life, and sufficient control drum worth [3].

2. Reactor Core Design

This study proposes a micro heat pipe reactor intended as a space power source, named the Space Integrated heatpipe REactor Unit System (SIREUS). Because SIREUS must achieve criticality within a limited core volume suitable for launch and deployment, selecting a fuel that can accommodate a high fissile inventory per unit volume is essential. Accordingly, this work adopts nitride fuel, which is advantageous for compact fast reactors due to its high uranium and plutonium atomic densities and high thermal conductivity compared to conventional UO₂ fuel. Uranium plutonium nitride (UPuN) was selected as the specific fuel candidate. The use of UPuN allows for the recycling of plutonium recovered from spent nuclear fuel reprocessing, thereby reducing natural uranium consumption, contributing to

improved nuclear waste management. For core performance evaluation, the reference fuel composition was defined as U_{0.7}Pu_{0.3}N based on the heavy metal atomic fraction, utilizing non-enriched U238 and Pu239 as the primary fissile isotope. Analysis of core performance with varying Pu atomic fractions indicated that a composition with a 30% Pu atomic fraction provides the most reasonable balance between the nominal operating and controlled conditions.

Table I: Calculated k_{eff} as a function of Pu atomic fraction.

Fuel	k_{eff}	
	Normal	controlled
U _{0.75} Pu _{0.25} N	1.1445	0.7940
U _{0.7} Pu _{0.3} N	1.2549	0.8734
U _{0.65} Pu _{0.35} N	1.3472	0.9494

std ± 18~20pcm

The reflector increases neutron economy by returning leaking neutrons to the core, thereby reducing the effective core size required to achieve criticality. This leakage reduction effect is important for compact fast reactors, where neutron leakage is significant. Since the reactor developed in this study is a fast-spectrum system, Fig. 1 compares the neutron cross-section characteristics of representative low atomic number (Z) reflector candidates in the fast-energy range. [4]

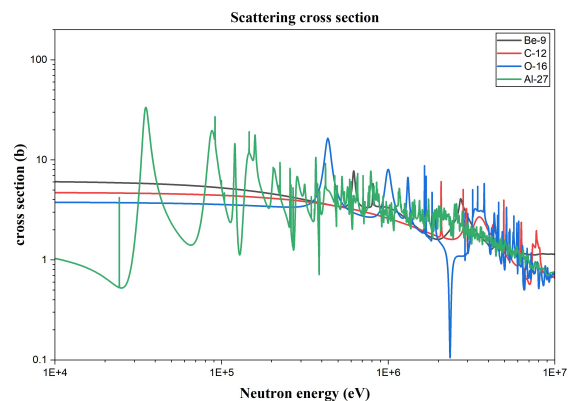


Fig. 1. Neutron scattering cross section of low Z material [4]

While Be-9 exhibits a low absorption cross section and a high scattering cross section favorable for leakage reduction, BeO was ultimately selected as the reflector

material based on engineering feasibility. BeO demonstrates superior structural integrity and high-temperature stability under space reactor operating conditions, and is considered more practical in terms of toxicity management and manufacturing processes compared to metallic Be.

Reactivity control was designed by referencing the rotating drum control concept under development at KAERI. The control drums are arranged annularly around the outer region of the core, and reactivity is regulated by rotating the drums to vary the fraction of absorber facing the core. As illustrated in Fig. 2, the fuel region is located at the core center and is surrounded by six cylindrical control drums. Each drum contains a crescent-shaped B₄C absorber, using B₄C enriched to 90wt% in B10. The design parameters are provided in Table II.

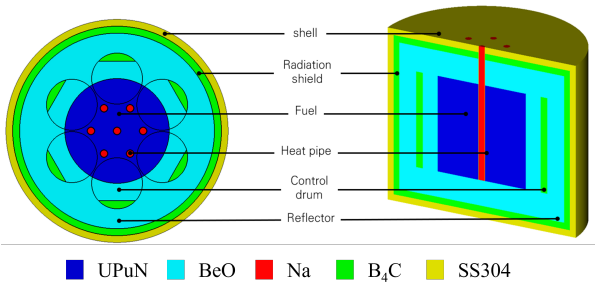


Fig. 2. Overview of SIREUS

Table II: Design parameters of SIREUS

Feature	Value
Power	30 kWth
Weight	874.3kg
Core size	64cm (D), 64cm(H)
Fuel size	30cm (D), 30cm (H)
Heat pipe	2.2cm(D), 47cm (H)
Reflector	13cm thick
Radiation shield	2cm thick
Shell	2cm thick

3. Neutronics analysis for the SIREUS

All neutronics calculations were performed using SCALE 6.3.1 with continuous-energy cross sections based on ENDF/B-VIII.0[7]. The Monte Carlo eigenvalue calculations used 50 inactive cycles and 2,000 active cycles, with 10,000 neutron histories per cycle. All standard deviations were less than 20 pcm. Since the target operating temperature of the space reactor is 1000 K, all calculations were performed at 1000 K.

The neutron spectrum of SIREUS was evaluated, as shown in Fig. 3, confirming that the reactor operates in a fast spectrum. This is because no moderator is employed, as intended in the design.

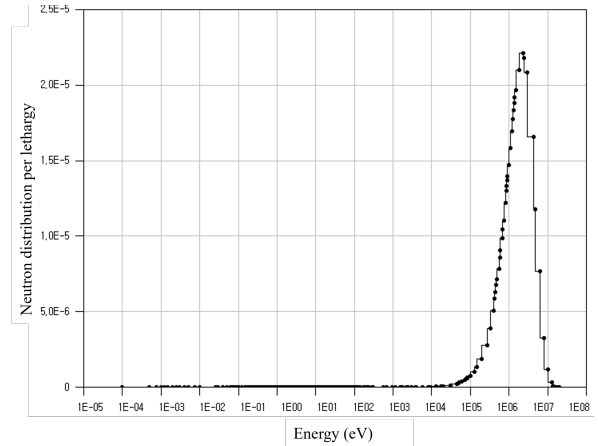


Fig. 3. Neutron spectrum

As shown in Fig. 4, the k_{eff} value decreases approximately linearly as the control drum rotation angle increases, reaching 0.8734 at the maximum angle of 180°. This demonstrates that the CD alone can provide sufficient shutdown capability, eliminating the need for gravity-dependent control functions such as control rods and thereby indicating suitability for operation in space.

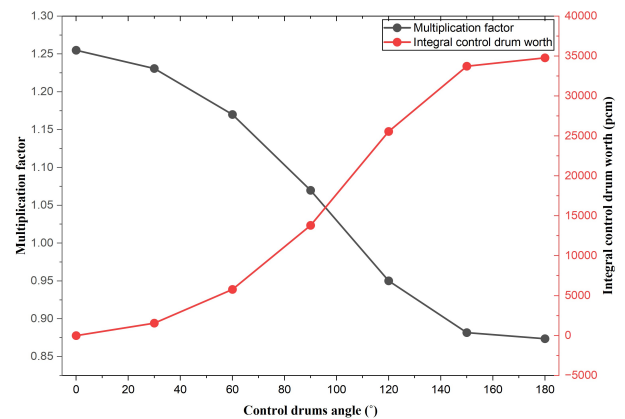


Fig. 4. Multiplication factor and integral control drum worth as a function of control drum angle

Also, calculations were performed assuming a failure of the CD drive system that causes the drum rotation to stop. As shown in Fig. 5, the analysis cases were defined for cases in which failures occur in one to three control drums, and the calculations were carried out accordingly. As summarized in Table III, the results confirm that subcriticality is safely maintained for up to two control drum failures. However, the calculated absorber worth does not show a monotonic trend with the number of failed control drums. This is because the control drum worth is strongly affected by the spatial arrangement of the absorber sections as well as by the number of failed drums. Specifically, in 2CD-case1 and 3CD-case3, the absorber sections are closely adjacent to one another, leading to a reduced worth compared with other configurations. This reduction can be explained by the shadowing effect, in which the neutron

absorption by one absorber diminishes the additional absorption available to the neighboring absorber.

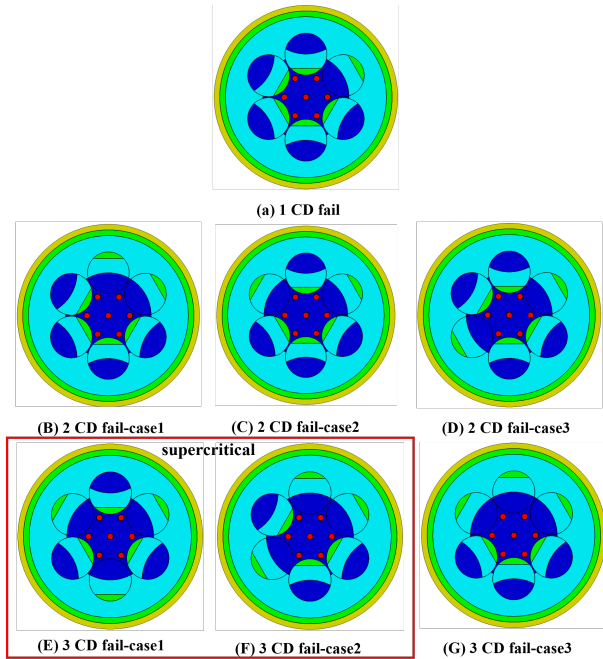


Fig. 5. Control drum actuation failure case

Table III. The k_{eff} results of the failure case

Failure case	Multiplication factor	Worth (pcm)
1CD	0.88783	3294
2CD-case1	0.98518	2181
2CD-case2	0.93842	2687
2CD-case3	0.93404	2737
3CD-case1	0.98449	2188
3CD-case2	1.01711	1863
3CD-case3	1.05728	1489

std \pm 20 pcm

The reactor inherent safety characteristic, namely the fuel temperature coefficient (FTC), was evaluated. Table IV summarizes the calculated k_{eff} values as a function of fuel temperature. The results show that k_{eff} decreases as the fuel temperature increases, indicating negative reactivity feedback primarily due to Doppler broadening. Overall, the negative FTC contributes to inherent safety by mitigating reactivity increases during operation, thereby helping limit power excursions and enhancing reactor stability.

Table IV. Reactivity coefficients

Parameters		Value
FTC	900-1000K	-0.3151pcm/K
	1000-1100K	-0.1351pcm/K

std \pm 20 pcm

As shown in Fig. 6, based on the depletion calculation

result performed at the full-power condition of 30 kWth, the proposed reactor is expected to enable long-term operation for more than 20 years. Since the operating duration required for space exploration missions is relatively short compared to this timescale, these results indicate that, from a mission perspective, the system can serve as a unlimited long-term energy source.

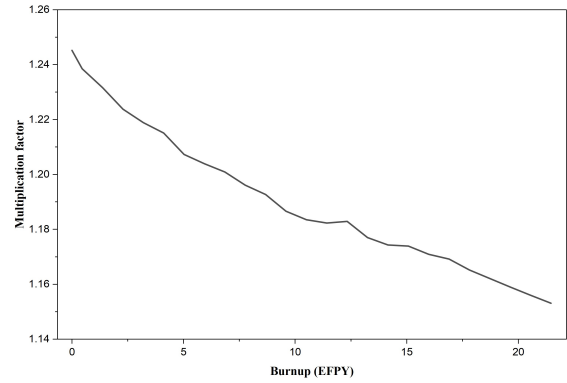


Fig. 6. Depletion Calculation result

4. Conclusion

This study presented the conceptual design and neutronic analysis of SIREUS, a 30 kWth monolithic heat pipe reactor designed for long-term space missions. By adopting UPuN fuel with a 30% Pu fraction, the reactor achieves sufficient criticality while maintaining a compact core size. The neutronic evaluations using SCALE 6.3.1 confirmed that the reactor operates in a fast spectrum and provides high reliability through a passive heat removal system. The control drum system demonstrated robust shutdown capability with a k_{eff} of 0.8734 at 180°, and subcriticality was maintained even under a two-drum failure scenario. Furthermore, the combined negative feedback from the FTC (-0.135 to -0.315pcm/K). These results indicate that SIREUS is a promising candidate for a sustainable and resilient energy source for future space exploration. Based on these findings, it is expected that this study will provide valuable insights and contribute to the design and optimization of future space nuclear reactors.

Acknowledgments

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