Conceptual Design of LBE-Cooled Subcritical Reactor-Based Nuclear Battery

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1. Introduction

With the increasing interest in deep-space exploration, nuclear energy is gaining importance due to its high energy density and reliability. Figure 1 shows one of the most successful applications: the Radioisotope Thermoelectric Generator (RTG). The Multi-Mission RTG (MMRTG) has powered several space missions, including the Mars rovers Curiosity and Perseverance. This RTG is designed to generate about 100watts of electric power.

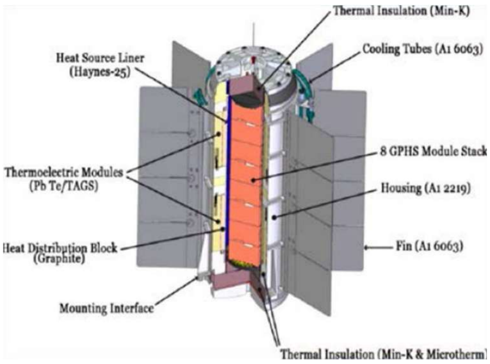

Fig. 1. Cutaway view of the MMRTG [1]

However, the increasing complexity of space missions and the plan of manned missions require higher power levels, which can not be obtained from the RTG. A Space Nuclear Reactor (SNR) is considered a promising future power source for advanced missions to replace the traditional RTG. However, designing a fission-based space reactor presents challenges, such as complex control mechanisms and criticality safety concerns. To overcome these issues and leverage the advantages of both SNR and RTG, we've proposed a subcritical reactor-based nuclear battery.

A subcritical reactor is a system driven by an external neutron source. There are several ways to generate neutrons, particularly if a particle accelerator is used, the system is called Accelerator Driven System (ADS). However, operating a particle accelerator requires a significant amount of energy. Thus, a radioisotope-based neutron source was chosen to operate a subcritical reactor in this study. Due to the physics of a subcritical reactor, the nuclear battery proposed in this study offers several advantages. First, no control mechanisms are required, and there is no possibility of criticality accidents because the fission chain reaction is not self-sustainable in the system. Second, fission energy is about 2 to 3 orders of magnitude higher than radioactive decay energy, leading to a higher power output.

2. Reactor Concepts and Methods

The nuclear battery designed in this study is a subcritical reactor driven by a ^{232}U-Be neutron source. The neutron source has a 14cm-diameter and 14cm-height cylindrical shape. ZrH_2 moderator and UN fuel cover the neutron source radially, while two axial BeO reflectors, each with a thickness of 20cm, are located to reduce the neutron leakage.

Outside of the core is enclosed by liquid-state Lead-Bismuth Eutectic (LBE) to remove the heat from the reactor core. The coolant flows through the natural circulation without any active pumping mechanism. LBE exchanges heat through a thermoelectric generator (TEG) to generate electricity. Since effective heat removal on the cold side of the TEG is crucial, fin structure is installed. Figure 2 shows a 3D model of the nuclear battery.

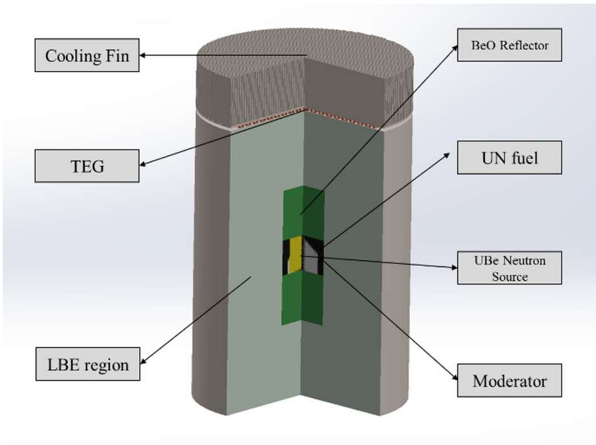

Fig. 2. 3D cutaway view of the proposed nuclear battery.

2.1 Reactor Core

This section covers the determination of the neutron source, fuel material, and moderator.

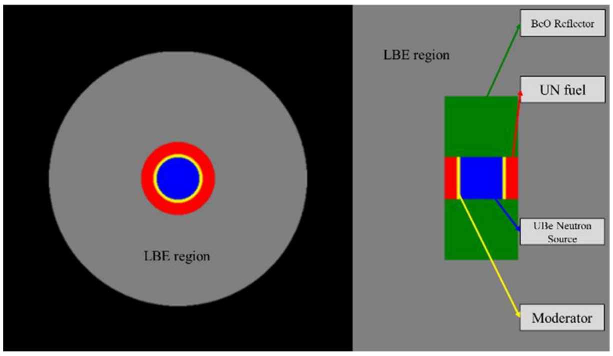

Fig. 3. Cross-sectional views of the nuclear battery.

Not only the fuel composition but also the radioisotope neutron source plays a crucial role in the subcritical system. The output power of a nuclear battery strongly depends on the neutron source strength, which means its lifetime is determined by the neutron source's longevity. Table I shows several neutron sources along with their half-lives and neutron yields. Except for ^{252}Cf, the other sources utilize the (α, n) reaction of Beryllium. Considering both half-life and neutron yield, the ^{232}U-Be source has a half-life of about 70 years and the greatest yield, except for ^{252}Cf and ^{228}Th-Be which have half-lives of less than 3 years. Figure 4 and Figure 5 show the neutron spectrum and source strength change with time of ^{232}U-Be source, respectively.

Table I: Typical Radioisotope Neutron Source [2]

Type of neutron source	Half-life (years)	Neutron Yield ($n\ g^{-1}s^{-1}$)
^{252}Cf	2.56	2.32×10^{12}
^{210}Pb-Be	22	1.24×10^{8}
^{226}Ra-Be	1620	1.10×10^{7}
^{228}Th-Be	1.91	1.08×10^{10}
^{232}U-Be	69	3.131×10^{8}
^{238}Pu-Be	86.4	4.66×10^{7}
^{241}Am-Be	458	5.89×10^{6}

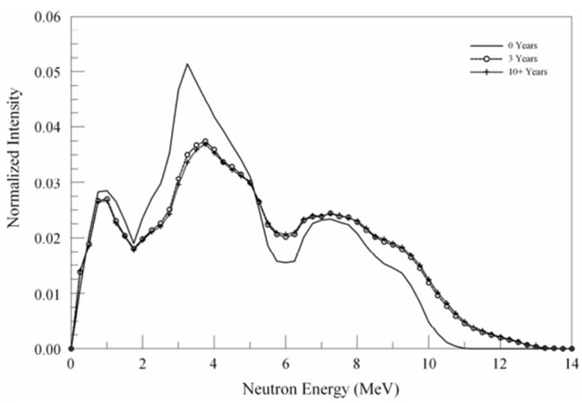

Fig. 4. Neutron spectrum of ^{232}U-Be source. [3]

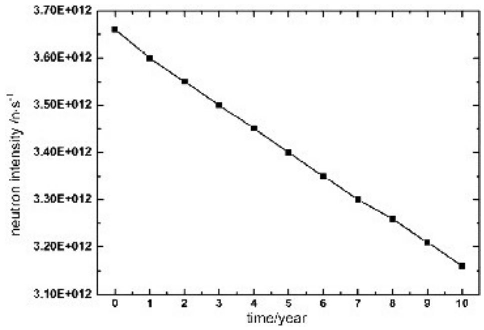

Fig. 5. Change of source strength of ^{232}U-Be with time. [2]

As shown in Figure 5, the source strength doesn't drop significantly for 10 years. Thus, the lifetime of the battery is mainly affected by the amount of fuel remaining.

It is crucial to determine the proper fuel composition to make the battery more compact. We can expect that high density of ^{235}U makes the battery more compact and light weight. The physical properties of typical fuel materials are shown in Table II. Except for U-Metal, other fuel materials are able to withstand temperatures above 2000°C, making them capable of generating higher thermal efficiency of the system. UN has the highest uranium density. Therefore, the reactor core consists of UN enriched to 19.75% w/o HALEU for nuclear non-proliferation.

Table II: Type of Nuclear Fuel Composition [4]

Fuel Material	U-Metal	UO_2	UN	UC
Density (g/cm^3)	19.04	10.97	14.32	13.63
Uranium Density (g/cm^3)	19.04	9.67	13.60	12.97
Thermal conductivity ($W/cm \cdot K$)	32	3.6	23	21
Melting Point (°C)	1133	2800	2390	2800

Most of the commercial reactors utilize H_2O as a moderator because of the high moderating power of Hydrogen. However, in the space environment or extreme condition, using H_2O becomes challenging. Thus, metal hydrides are considered as alternative moderator materials. As shown in Table III, ZrH_2 can be used because it has the greatest moderating power after H_2O.

Table III: Type of Moderator [5]

	Slowing-down Power	Moderating ratio
TiH_2	1.85	6.3
ZrH_2	1.45	55
LiH	1.2	3.5

YH_2	1.2	25
ThH_2	1.0	5.2
H_2O	1.35	70

2.2 Coolant

Liquid metal-cooled reactor can operate at much higher temperatures than a water-cooled reactor. The maximum thermodynamic efficiency is determined by the ratio between temperatures of the hot-side and cold-side. Compared to the sodium-based liquid metal, lead-based coolant has higher operating temperature. However, pure lead has too high melting point (327 °C). Thus, Bismuth could be mixed with pure lead to form eutectic fluid with Pb (44.5%a/o) and Bi (55.5%a/o) to obtain the significantly reduced melting point (123.5 °C).

Also, if the battery is used for a manned mission, radiation shielding becomes a crucial issue for crew members. In this perspective, lead has great radiation shielding properties, allowing the battery to operate with minimum extra shielding material.

2.3 Thermo-Electric Generator (TEG)

Heat energy could be converted into electricity directly through the TEG. The basic principle of TEG is the Seebeck effect, where a temperature gradient causes an electric potential. The TEG has no moving parts, and its high reliability makes it suitable for converting radioisotope decay heat into electricity for a RTG. The performance of the TEG is expressed as device Figure of Merit number ZT, which is defined as Eq. 1.

$$ZT = \frac{\alpha^2}{\rho\lambda}T \qquad (1)$$

where α is the Seebeck coefficient, ρ is the electrical specific resistance, λ is the thermal conductivity. Also, the maximum efficiency is computed as Eq 2.

$$\eta_{\text{th,max}} = (1-\tfrac{T_c}{T_h})\frac{\sqrt{1+Z\overline{\overline{T}}}-1}{(\sqrt{1+Z\overline{\overline{T}}}+\tfrac{T_c}{T_h})} \qquad (2)$$

3. Results and Analysis

3.1 Fuel

Neutronic calculations were performed by open-source Monte-Carlo software OpenMC with 1,000,000 neutron histories. Two different calculation modes are used, eigenvalue mode to calculate multiplication factor and fixed source mode to calculate heat deposition depending on the fixed neutron source. For the eigenvalue mode, 50 inactive and 150 active cycles were used. Also, it is confirmed that the uncertainties were less than 50pcm for all cases.

To design the subcritical core, the UN radius was adjusted to find the geometry that maximizes the multiplication factor while keeping it below 1. As shown in Figure 6, UN radius was determined as 11cm.

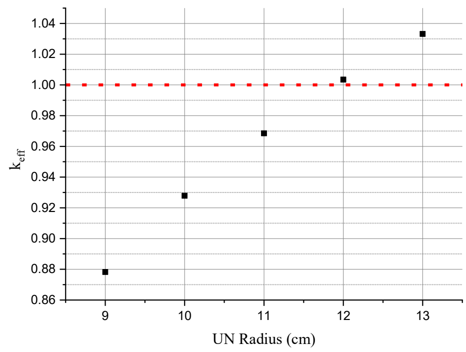

Fig. 6. Fuel thickness-dependent multiplication factor.

To minimize the amount of LBE to reduce unnecessary weight, a fixed source calculation was done while the radial thickness was reduced from 30cm to 22.5cm by 2.5cm steps. Since the outside of the LBE was set as a vacuum boundary condition, the LBE layer significantly reflected neutrons. Therefore, the thickness could only be reduced by a small amount. Power changes due to LBE thickness change is described in Table IV.

Table IV: Effect of LBE Thickness on Heat Generation

LBE Thickness (cm)	Fuel (W)	LBE (W)	Reflector (W)	Total (W)
30	1219.8	5.8	1.1	1226.7
27.5	1043.1	5.0	0.9	1049.0
25	778.7	3.8	0.5	783.1
22.5	563.2	2.8	0.3	566.2

3.2 Coolant

The thermohydraulic calculation was done using ANSYS Fluent computational fluid dynamics (CFD) software. An unstructured mesh was generated using the ANSYS Meshing tool, consisting of hexahedral elements. The total number of cells varied depending on the liquid lead-bismuth eutectic (LBE) layer thickness, with approximately 29 million, 34 million, 38 million, and 44 million cells for LBE thicknesses of 22.5cm, 25cm, 27.5cm, and 30cm, respectively. Thermodynamic properties were obtained from the OECD-NEA report [6]. These properties were input as polynomials or functions as temperature to calculate temperature-driven phenomena such as natural circulation. Heat source is computed from the Monte-Carlo code for each component and input into CFD as a volumetric heat generation term. Assuming that the bottom and side walls were thermally insulated, heat exchange occurs only at the top surface, which is connected to the TEG.

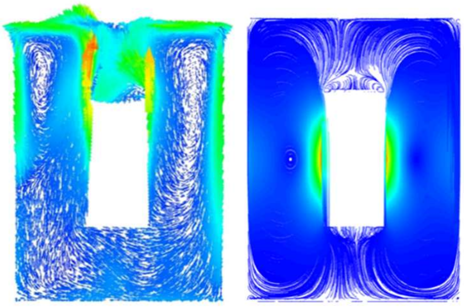

Fig. 7. Velocity vector and stream line of LBE computed by Ansys Fluent.

In Figure 7, it is obvious that heat from the core create temperature gradients in the LBE, inducing density differences that drive natural circulation flow due to the thermal expansion and buoyancy of LBE. Also, we could observe the recirculation, where buoyancy-driven flow forms distinct vortices.

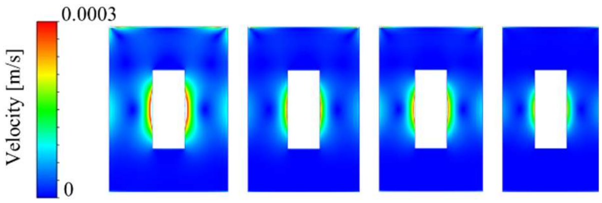

Fig. 8. Magnitude of LBE velocity depends on LBE thickness. (30cm, 27.5cm, 25cm, 22.5cm)

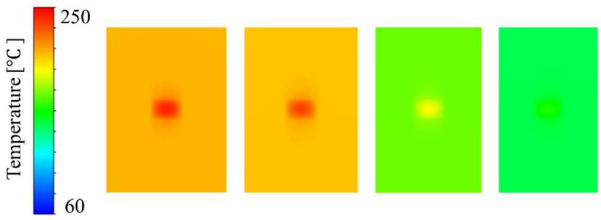

Fig. 9. Temperature depends on LBE thickness. (30cm, 27.5cm, 25cm, 22.5cm)

In this simulation, the LBE thickness significantly affects the total heat input power. The maximum and minimum temperatures of the fuel, LBE, and reflector as the LBE thickness decreases are shown in Table V. It is obvious that thinner LBE layers lead to lower temperatures across all components, highlighting the role of LBE in maintaining heat retention and the overall efficiency of the battery.

Table V: Maximum and minimum Temperature of Fuel, LBE and BeO reflector

LBE Thickness (cm)		Fuel (℃)		LBE (℃)		Reflector (℃)	
30	Min	211	208	209	211	208	209
	Max	226	209	220	226	209	220
27.5	Min	208	205	206	208	205	206
	Max	220	206	215	220	206	215
25	Min	172	169	170	172	169	170
	Max	181	171	177	181	171	177
22.5	Min	114	141	143	114	141	143
	Max	151	144	149	151	144	149

4. Conclusions

In this study, a new LBE-cooled subcritical reactor-based nuclear battery concept was proposed It was analyzed both in neutronics and thermo-hydraulics. Although it could only operate under a gravitational environment due to its reliance on natural circulation, it has the potential to serve as a power source for outer planets such as Mars. For this application, CFD calculations with different gravitational accelerations should be conducted. Also, the service life of the battery needs to be estimated more precisely, including depletion of fuel. Furthermore, the current neutron source size was fixed to 14cm diameter and 14cm height cylindrical shape, but it should be optimized to minimize the size and weight.

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