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Neutronic Feasibility of Micro Molten Salt Metal Reactor (MSMR) as a Fission Surface Power (FSP) System

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1. Introduction

To enable exploration of extraterrestrial planets such as Mars, the establishment of an intermediate moon base is critical. Such a power system should operate reliably for a sufficiently long period without the need for additional resources and should be able to operate regardless of the surrounding environment. Due to the limited storage capacity of current spacecraft, the size of the system must also be compact and thus requires high energy density. In these regards, nuclear fission energy is an attractive option and, consequently, international efforts are being made to develop a “space reactor”.

A fission surface power (FSP) system is a nuclear fission reactor designed to operate on extraterrestrial surfaces. The term originates from NASA’s fission surface power project, which has currently evolved into the Kilopower project [1]. This project aims to operate a 40 kWe fission power system on the moon for at least 10 years starting from the late 2020s, and NASA has selected three reactor designs in June 2022 for this purpose [2].

In this study, we propose our own novel FSP system based on the Molten Salt Metal Reactor (MSMR), which is an innovative reactor design previously developed by our group [3]. The MSMR is a Molten Salt Reactor (MSR) that uses U-Fe alloy liquid metal for fuel in the active core which is surrounded by a layer of molten salt to trap “salt-seeking” fission products. The MSMR is also a fast reactor and thus uses High-Assay Low-Enriched Uranium (HALEU) fuel. The MSMR has all of the typical advantages of MSRs and fast reactors, such as high passive safety and high conversion ratio to name a few. Some radical changes were made to the original design and neutronics model to adopt the MSMR as an FSP system and the feasibility of this new design was evaluated in this study.

2. MSMR model for Space Applications

2.1 MSMR design

The current MSMR design utilizes U-Fe alloy liquid metal fuel. Due to the high mass fraction (89%) of uranium of the fuel, the critical mass was significantly reduced. This fraction corresponds to the lowest melting point on the U-Fe phase diagram, which is 1000K. While the longest fuel life is obtained with 12% uranium enrichment, the maximum enrichment of HALEU fuel (19.75%) was used to minimize the fuel volume.

Considering that liquid uranium acts as fuel, selecting a solid metal reactor vessel becomes essential. However, the different phases of metals can undergo corrosive chemical reactions when coming in contact. These reactions are intensified at the high temperatures at which the MSMR operates. To mitigate this corrosion, we selected a reactor vessel made of tantalum and coated it with tantalum carbide (TaC) [2]. TaC is known to exhibit robust corrosion resistance against salt [4].

The conditions on the Moon and Mars are vastly more extreme than on Earth, demanding system adaptations and simplifications. Additionally, to reduce the size of the reactor, the heat removal system for the space version of the MSMR is designed around a heat pipe paired with a Stirling engine, as depicted in Fig. 1.

The heat pipes extract heat from the reactor core and channel it to the Stirling engine. They are externally attached to the tantalum wall. Potassium is the working fluid. A heat pipe with an outer diameter of 22mm has the capability to dissipate as much as 20.4 kW of heat [5]. A thin layer of salt covers the external surface of the tantalum wall, facilitating heat transfer to the attached external heat pipe and acting as a protective barrier against potential fission product leakage during accidents. Thus, the external heat pipe maintains contact with the tantalum wall while being immersed in the salt.

Regarding heat dissipation from the Stirling engine condensers, we suggest using a NaK eutectic cooling loop. This loop is equipped with electromagnetic pumping and directs heat toward the system radiator.

As depicted in Fig. 1, the reflector is enveloped by radiation shielding (light purple). The design of this shielding adheres to the NASA's fission surface power statement of work (SoW) design requirement (DR-3) [6]. The reactor is built on land so there is no need for a bottom shield.

The region colored in yellow, while made of the same stainless steel as the reflector, serves as the reactivity control device. A detailed discussion of this component is presented in Section 3.2.

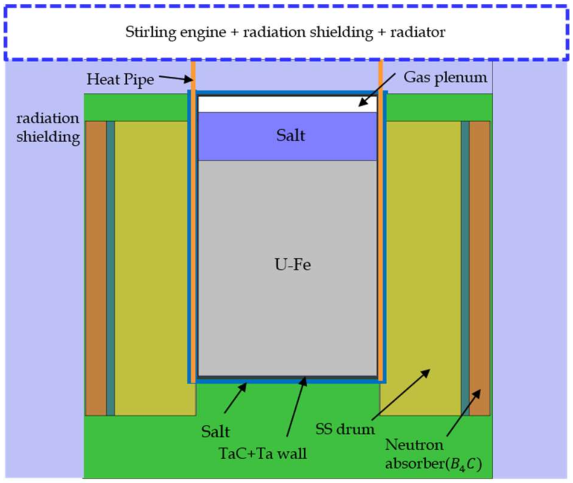

Fig. 1. Schematic of the MSMR FSP system

2.2 Neutronic calculation model

To conduct neutronics calculations, a modified neutronics model was devised from the original one. The heat pipes, Stirling engine, graphite pebbles and shielding material do not significantly affect the neutronics and were removed from the model. A schematic of the neutronic calculation model is shown in Fig. 2.

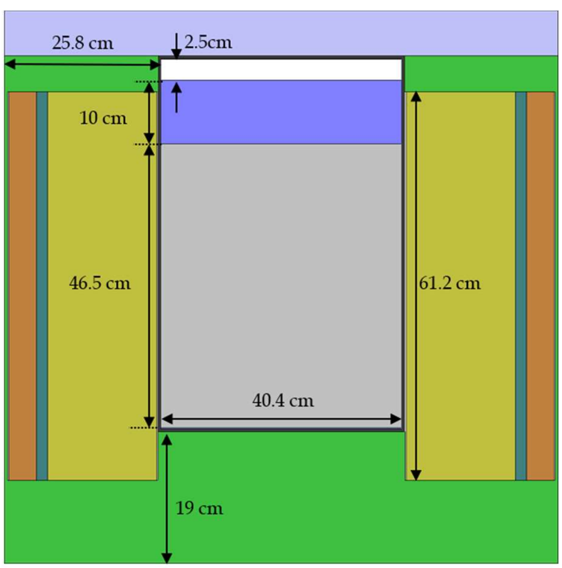

Fig. 2. Schematic of the neutronics calculation model

The fuel has a diameter of 40.4 cm, a height of 46.5 cm, and a fuel inventory of 910.9 kg at normal operating temperature (1000 K). The salt layer has a diameter equal to that of the fuel, and the height is 10 cm. The gas plenum is 2.5 cm. The thickness of the radial direction reflector is 25.8 cm, and the thickness of the bottom reflector is 19 cm. The material of the reflector is stainless steel. The H/D ratio of the fuel is 1.15, which is slightly different from the optimum value of 0.95, but it is set to 1.15 because of the reactivity control problem to be discussed in section 3.2.

3. Methods and Numerical Results

In this section, we performed computational analyses using the Serpent2 Monte Carlo code and the ENDF/B-VII.1 library. The calculations were made under the assumption that, at full power, the temperature of the fuel is 1273 K, while that of the salt and the tantalum wall are 973 K, and the remaining components are assumed to be at room temperature, 298 K.

The kinetic parameters are summarized in Table I. The effective delayed neutron fraction is 751 pcm, and due to the reactor being a fast spectrum reactor, the prompt neutron lifetime is notably short. At the Beginning of Life (BOL) conditions, the k_{eff} value at full power is 1.00649. Consequently, the design is crafted to prevent the excess reactivity from achieving prompt criticality.

Table I: Kinetic parameters of MSMR

k_{eff}	Effective delayed neutron fraction [pcm]	Adjoint-weighted prompt neutron lifetime [ns]
1.00649 ± 9E-05	751.2 ± 1.25	46.34 ± 0.15

Fig. 3 depicts the normalized power density. The central region exhibits the highest power density, which decreases towards the periphery.

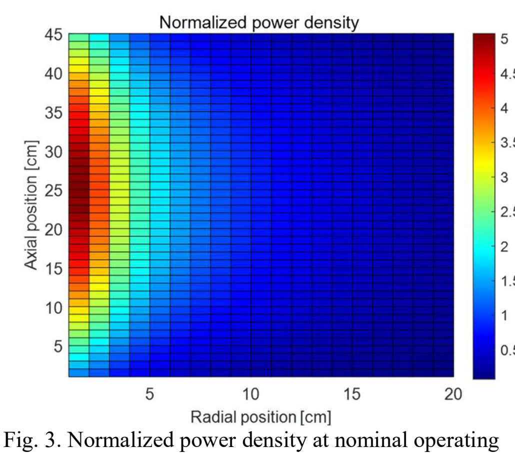

Fig. 3. Normalized power density at nominal operating conditions.

3.1 Depletion calculation

The results for the depletion calculations are shown in this section. Fig. 4 illustrates the depletion calculations for both 300 kWth and 500 kWth conditions. The anticipated operational lifespans are 32 years for the 500 kWth setup and 44 years for the 300 kWth setup. At the

Beginning of Life (BOL) conditions, the initial excess reactivity stands at 644.8 pcm. As the reactor is designed to operate without refueling, the reactor lifespan is defined as the time it takes from the start of operation to reach zero excess reactivity. The blue and red curves represent the results for 500 kWth and 300 kWth, respectively. Depletion calculations were conducted in 5-year intervals.

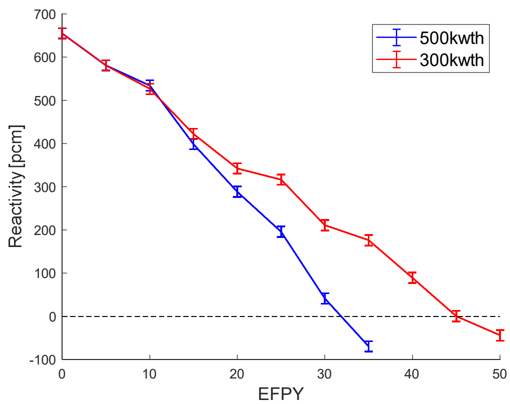

Fig. 4. Reactivity as a function of depletion for both the 300 kWth and 500 kWth scenarios.

Fig. 5 depicts the variation of conversion ratio and burnup over the course of the depletion calculation. The blue line represents the conversion ratio, while the red line corresponds to the burnup. Additionally, the left y-axis represents the conversion ratio, whereas the right y-axis indicates burnup. Regarding the conversion ratio, it is about 0.36 and does not change meaningfully over time. The burnup amounts to approximately 6 MWd at the end of operation.

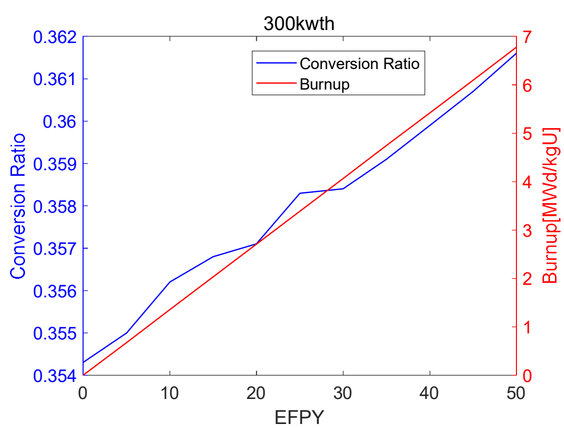

Fig. 5. Change of conversion ratio and burnup over time.

Fig. 6 illustrates the variation in the effective delayed neutron fraction over the course of the depletion calculation. Starting from an initial value of 750 pcm, there is a modest decrease, with a total reduction of approximately 10 pcm throughout the reactor lifetime.

Fig. 7 presents the depletion calculation for a 300 kWth output, factoring in variable removal of fission products from the fuel. Assuming that the reference is a state in which the fission product is not removed, 0% indicates complete removal of noble gasess, 50% indicates complete removal of noble gases along with 50% removal of fission products, and 100% indicates complete removal of noble gases and fission products. Burnup calculations were conducted in 3-year intervals, with removal occurring once every three years. These results imply a potential extension of the reactor's lifespan by up to 4 years.

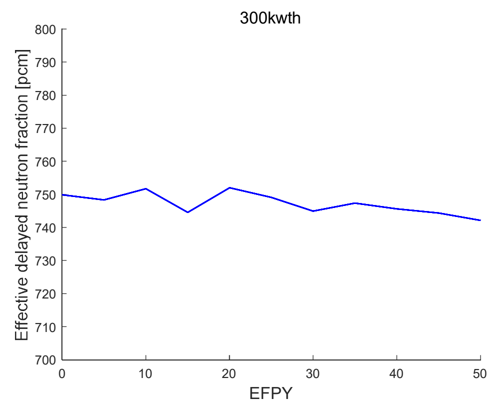

Fig. 6. Variation of effective delayed neutron fraction over time.

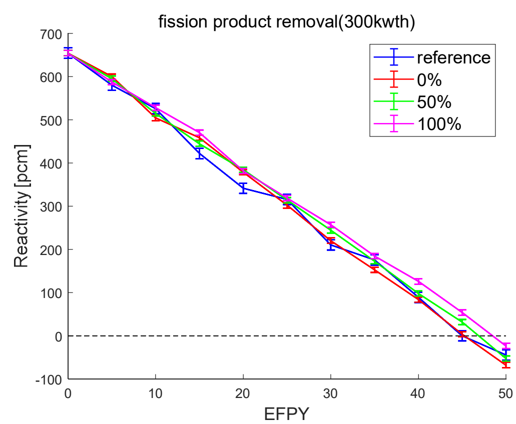

Fig. 7. Depletion calculation with varying levels of fission product removal

3.2 Reactivity Control

The MSMR uses a liquid metal fuel. Near the solidifying point during reactor cooling, there is a noticeable spike in reactivity. Given that outer space temperatures encompass both cryogenic temperatures and room temperature (293 K), it becomes crucial to conduct a thorough evaluation factoring in this temperature range.

Reactivity control in the MSMR is achieved through the rotation of drum-shaped control devices with neutron-absorbing pads on one side surrounding the core. When the neutron-absorbing pad is positioned further from the core, more neutrons get reflected before being absorbed by the pad. A total of eight drums are placed 45 degrees apart from each other right outside of the core. The reactivity worth of the drums can be estimated through comparison of reactivity calculations between situations with different drum rotation levels . The drums are made of stainless steel and have a diameter of 24.9 cm.

The neutron absorber in the pad is 90 wt% B_4C. Inwards to this B_4C pad, a 2 cm thick BeO pad is situated to enhance the neutron absorption efficiency of the B_4C. The B_4C and BeO pads are positioned in a fan-shaped configuration spanning a 120-degree angle. In Fig. 8, the B_4C pad is highlighted in orange, while the BeO pad is depicted in blue.

Fig. 9 shows a zoomed in view of region marked by the red box in Fig 8 . The minimum separation between the drums is 5 mm. There is a 2 mm air gap at the outermost region of each drum. This results in a total distance of at least 9 mm between each drum.

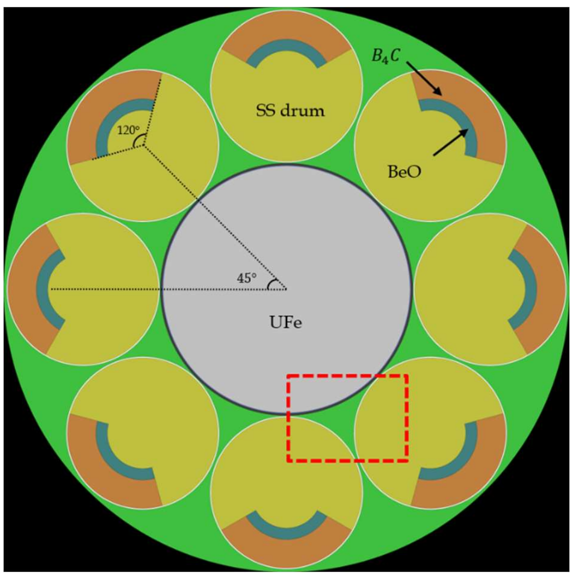

Fig. 8. A cross-sectional image of the reactor at the fuel section.

We evaluated k_{eff} and reactivity four distinct situations represented by their temperature: 1273 K represents full power operation, 1000 K represents operation at fuel temperature just below freezing point where the fuel has become a solid, 273 K represents room temperature, 25 K represents a situation at an extremely low temperature such as at the poles of the Moon. The results are shown in Table II. $\Delta\rho$ represents the reactivity difference compared to full power.

As seen in Table II, the density of the fuel significantly increases as it transitions from a liquid to a solid at 1000K, resulting in considerable increase of excess reactivity. Unlike on the Earth, temperatures in space can drop dramatically. Simulation of this type of situation using the 25 K condition shows the magnitude of excess reactivity increase that can be expected. To offset this reactivity, a substantial amount of drum worth is required. Evaluations regarding this are summarized in Table III.

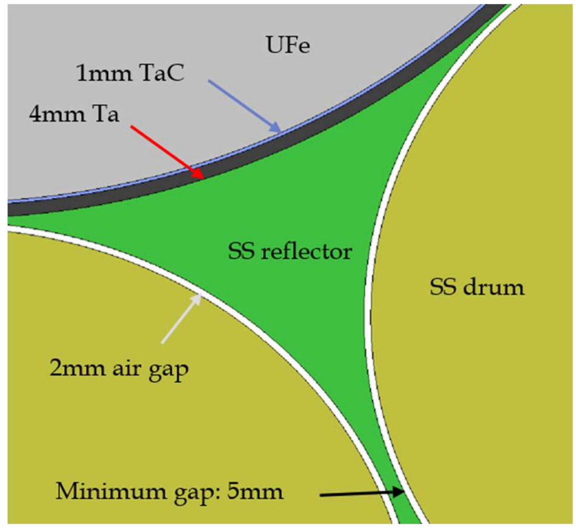

Fig. 9. An enlarged image of the red dashed box from Fig. 8.

Table II: Results for possible situations in outer space

	k_{eff}	Reactivity (pcm)	$\Delta\rho$ (pcm)
Full power (1273 K)	1.00649	644.8	0
Fuel freezing point (1000K)	1.03584	3571.2	2815.2
Room temperature (273 K)	1.03691	3677.4	2914.8
Extreme cold (25K)	1.03825	3810.4	3039.3

Table IV presents the shutdown margin. We compared two cases with target k_{eff} values of 0.99 and 0.995. Evaluations were conducted for the All Drums In (ADI) scenario, where all drums are oriented toward the fuel side, and the N-1 drum scenario, which assumes one of the drums is malfunctioning. Not only for k_{eff} = 0.995 but also for 0.99, there is a shutdown margin, indicating that the drum worth is evaluated to be sufficient.

Table III: Drum worth

	k_{eff}	reactivity	Drum worth
ADO	1.03825	3810.4	-
ADI	0.98306	-1723.2	5533.6
N-1 drum	0.98838	-1175.7	4986.1

Table IV: Shutdown margin

	k_{eff} = 0.99	k_{eff} = 0.995
ADI (pcm)	713.1	1220.7
N-1 drum (pcm)	165.6	673.2

4. Conclusions

In this research, we evaluated the feasibility of a novel MSMR design as a FSP system . Key components differentiating our design from others is the incorporation of heat pipes and Stirling engines. This not only simplifies the reactor design but also achieves a significant reduction in both size and weight. Depletion analysis revealed its impressive fuel efficiency, capable of lasting 32 years at 500 kWth and a remarkable 44 years at 300 kWth without the need for refueling, attributed to its superior conversion ratio. Essential operational parameters such as temperature feedback, shutdown margin, and the worth of the reactivity control device meet rigorous design criteria . While further evaluations concerning thermohydraulics calculations and material considerations are needed, our findings demonstrate the viability of the MSMR as a power supply system for space bases.

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