

Article

Preliminary Neutronic Design and Thermal-Hydraulic Feasibility Analysis for a Liquid-Solid Space Reactor Using Cross-Shaped Spiral Fuel

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Abstract

As the key technology of space exploration, space power has been a major area of international research focus. A lot of research work has been carried out around the world for the space nuclear reactor using the heat pipe, liquid metal and gas cooling methods. With the development of molten salt reactor in the Generation IV reactor system, molten salt dissolving fissile material and acting as a coolant at the same time has become a new cooling scheme, which provides new ideas for the design of space nuclear reactors. In this study, a novel reactor, the liquid-solid dual-fuel space nuclear reactor (LSSNR) was preliminarily proposed, combining the molten salt fuel and cross-shaped spiral solid fuel to achieve the design goals of 30-year lifetime and an active core weight of less than 200 kg. Monte Carlo neutron transport code OpenMC based on ENDF/B-VII.1 library was employed for neutronics design in the aspect of fuel type, cladding material, reflector material and the spectral shift absorber. Then, the thickness of the control drum absorber was optimized to meet the requirement of the sufficient shutdown margin, lower solid fuel enrichment, and 30-effective-full power-years (EFPY) operation lifetime. Finally, UC solid fuel with U-235 enrichment of 80.98 wt.% and B₄C thickness of 0.75 cm were adopted in LSSNR, and BeO was adopted as the reflector and the matrix material of the control drum. A spectral shift absorber Gd₂O₃ was used to avoid the subcritical LSSNR returning to criticality in a launch accident. The k_{eff} with the control drum in the innermost position is 0.954949, and the k_{eff} reaches 1.00592 after 30 EFPY of operation. The total mass of the active core is 158.11 kg. In addition, the thermal-hydraulic feasibility of LSSNR using cross-shaped spiral fuel was analyzed based on a 4/61 reactor core model. The structure of cross-shaped spiral fuel achieves enhanced heat transfer by generating turbulence, which leads to a uniform temperature distribution of the coolant flow field and reduces local temperature peaks. Based on the LSSNR scheme, some neutronic characteristics were analyzed. Results demonstrate that the LSSNR has strongly negative reactivity coefficients due to the thermal expansion of liquid fuel, and the fission gas-induced pressure meets safety requirements. One hundred years after the end of core life, the total radioactivity of reactor core is reduced by 99% and is 7.1305 Ci.



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1. Introduction

1.1. Background of Space Reactor and Cross-Shaped Spiral Fuel

At present, human space exploration activities are rapidly advancing with the development of science and technology. As a key enabling technology of space exploration, space power systems have attracted sustained interest from international researchers [1]. The application of nuclear energy in space exploration has also been extensively investigated worldwide. According to the method of nuclear energy utilization, space nuclear power is mainly divided into two categories. The first is radioisotope thermoelectric generator (RTG) [2,3], which converts the decay heat released by radioisotopes ^{238}Pu and ^{241}Am into electrical energy through thermoelectric conversion devices. Compared with RTGs, space nuclear reactors are capable of delivering significantly higher power levels (typically ranging from tens of kWe to MW scale), which makes them more suitable for high-power deep-space missions such as electric propulsion and planetary surface power systems. [4] Three main cooling methods are commonly employed in space nuclear reactors, including alkali metal (Na, K, Li) heat pipes [5], liquid metals (Na, NaK, Li) [6] and gases (He-Xe mixtures and CO_2) [7].

Extensive research has been conducted worldwide on the three aforementioned types of space nuclear reactors. The United States, Russia, Japan, and Europe, among others, have proposed dozens of space nuclear reactor design concepts, some of which have achieved space deployment [8–11]. In the new century, several studies on advanced space reactors have been initiated worldwide. The Massachusetts Institute of Technology (MIT) proposed a Martian surface reactor employing UN fuel with an enrichment of 33.1%, cooled by lithium heat pipes and with a thermal power of 1.2 MW [12]. Since 2004, the University of New Mexico has proposed conceptual designs for several space nuclear reactors, including SAIRS, HP-STMCs, SCoRe, and S4, using traditional cooling methods [13,14]. Based on the design concept of a prismatic high-temperature gas-cooled reactor, Tsinghua University proposed a lithium-cooled space reactor using dispersed UN fuel particles and investigated its neutronic characteristics [15].

With the development of Generation IV reactor systems, molten salt reactors (MSRs), in which molten salt simultaneously serves as both fuel carrier and coolant, have emerged as a promising concept, providing new approaches for the design of space nuclear reactors. Compared with other reactors, molten salt space reactors offer advantages such as compactness, high power density, and high thermoelectric conversion efficiency, and are suitable for applications in propulsion and planetary surface power systems. The Ohio State University proposed a preliminary design of a space molten salt reactor core based on a mixed molten salt fuel of $\text{LiF-BeF}_2\text{-UF}_4$ and performed criticality and temperature reactivity coefficient calculations using MCNPX. The results showed that due to the thermal expansion of fluorine salt, the fuel temperature coefficient reached $-0.016\ \$/\text{K}$. FLUENT was subsequently used to analyze fuel flow stagnation [16]. In Japan, a heat pipe-cooled molten salt space reactor based on $\text{UF}_4\text{-}^7\text{LiF-BeF}_2\text{-ZrF}_4$ fuel was proposed, and the core temperature at the beginning and end of the lifetime was evaluated using a heat balance model [17]. In China, Cui et al. [18,19] proposed a micro-space molten salt reactor scheme requiring 50 kWth, with a high negative feedback coefficient, and further developed effective control schemes. Yu et al. [20] proposed the M2SR-1 scheme, in which the upper part of the core is cylindrical and the lower part is hemispherical to reduce the fuel salt

load. Song et al. [21] proposed dual drum-controlled space molten salt reactor (D2-SMSR), which utilizes molten salt as fuel and heat pipes for cooling, and introduces an innovative reactivity control strategy with improved heat transfer performance, effective shutdown capability, and long operational lifetime. Xing et al. [22] study identifies optimal fuel assembly configurations that offer favorable neutronic performance, including negative coolant temperature coefficients and strategic advantages such as tritium-free NaF-ZrF₄ coolant. Li et al. [23] proposed a design scheme for molten salt reactors that combine liquid and solid fuels to attain compact structures with high-fuel consumption. To investigate the impact of fuel flow on burnup behavior in MSRs, a MATLAB R2018a-based MOCBurn code coupling MCNP5 and ORIGEN2 was developed, incorporating fuel mixing and geometry modeling techniques, and validated for both solid-fuel and molten salt systems [24].

To enhance the heat transfer performance of space reactors and further increase their power density, research on a novel cross-shaped spiral fuel (Figure 1a) has attracted significant attention in recent years. The European Fission Federation (EFF) has adopted a cross-shaped spiral fuel rod design, in which fuel rods with a cross-shaped cross section are arranged in a helical configuration to improve fuel utilization and energy output efficiency. The use of a new oxide dispersion strengthened (ODS) material as fuel cladding provides improved resistance to high temperatures and radiation, and reduces the risks associated with thermal expansion and cracking. Zhang et al. [25] compared the thermal-hydraulic properties of helical cross-shaped fuel with those of wire-packed fuel and found that the Nusselt number and friction factor increased by 4.6% compared with linear fuel. Conboy et al. [26] conducted an evaluation of helical-cruciform (HC) fuel assemblies for high-power light-water reactors and demonstrated that a boiling-water reactor (BWR) incorporating HC fuel assemblies with a twist pitch of 200 cm could achieve a 24% power uprate compared with a conventional BWR design. Fang et al. [27] found that the helical cross-shaped design enhances radial heat transfer and generates strong rotational flow near the wall, thereby reducing the hot spot factor. Chen et al. [28] proposed and validated geometric dimensionless parameters to modify friction factor and heat transfer coefficient correlations for helical cruciform fuel. Numerical simulations were performed to investigate the influence of geometric parameters, particularly twist pitch, on thermal-hydraulic characteristics. The established empirical correlations achieve errors below 10% over a wide range of Reynolds numbers, providing a reference for heat transfer and flow analysis in helical structures and reactor system modeling. Jiang et al. [29] systematically evaluates the accuracy and applicability of various numerical models in different flow regions based on experimental data from a hexagonal helical cruciform seven-rod bundle, identifies the optimal numerical simulation methods for each flow region, and provides guidelines for accurate numerical simulation of helical cruciform rod bundles.

1.2. Concept and Design Overview of the Liquid-Solid Dual-Fuel Space Nuclear Reactor (LSSNR)

Space reactor research mainly focuses on achieving long life, miniaturization, and high safety. In this study, a conceptual design of a liquid-solid dual-fuel space nuclear reactor (LSSNR) was proposed, which combines the advantages of conventional solid-fuel space reactors and molten salt reactors. The solid fuel uses highly enriched U-235 mainly to compensate for the decrease due to depletion. The liquid fuel contains only a small fraction of fissile material, and its density is strongly temperature-dependent. As the temperature increases, thermal expansion of the molten salt leads to a decrease in fuel density, which reduces the fissile material concentration and results in negative reactivity insertion. Similarly, the formation of voids further decreases the fuel density, enhancing the negative void reactivity coefficient. This effect provides an additional inherent safety feature compared with conventional solid-fuel reactors. In addition, most of the fission

products in the LSSNR are sealed in solid fuel, which greatly reduces the content and radioactivity of the fission products in the liquid fuel; therefore, no online fuel reprocessing is required. LSSNR adopts cross-shaped spiral fuel to enhance heat transfer performance by promoting liquid fuel mixing.

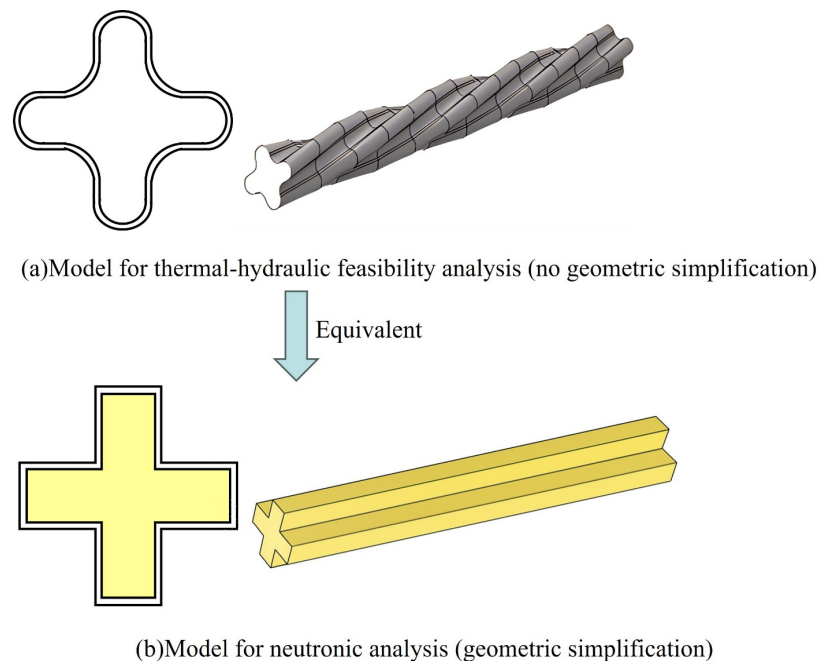


Figure 1. Model of the cross-shaped spiral fuel element.

In this study, a preliminary neutronic design and thermal-hydraulic feasibility analysis were performed for LSSNR with cross-shaped spiral fuel. The neutronic design targets include a lifetime of 30 effective full power years (EFPY), a thermal power of 1 MW, and an active core mass of less than 200 kg. The Monte Carlo neutron transport code OpenMC based on ENDF/B-VII.1 library was employed for neutronic calculations. The fuel type, cladding material, reflector material, spectral shift absorber, and the thickness of control drum absorber were optimized to achieve sufficient shutdown margin, reduced solid fuel enrichment, and a 30 EFPY operational lifetime. Finally, UC solid fuel with U-235 enrichment of 80.98 wt.% and B₄C absorber thickness of 0.75 cm were determined. BeO was adopted as reflector and matrix material of control drum. A spectral shift absorber Gd₂O₃ was introduced to prevent the subcritical reactor from returning to criticality during a launch accident. The effective multiplication factor (k_{eff}) with control drum in the innermost position is 0.954949. The k_{eff} reaches 1.00592 after 30 EFPY operation. The total mass of the active core is 158.11 kg. In addition, the thermal-hydraulic feasibility was analyzed by COMSOL Multiphysics software 6.3. The structure of cross-shaped spiral fuel achieves enhanced heat transfer by generating turbulence, leads to a uniform temperature distribution of the coolant flow field, and reduces local temperature peaks. For the preliminary LSSNR design, key neutronic characteristics were analyzed. The results indicate that the LSSNR exhibits strongly negative reactivity coefficients due to the thermal expansion of the liquid fuel, and that the fission gas-induced pressure meets safety requirements. Furthermore, 100 years after the end of core life, the total radioactivity of the reactor core is reduced by 99%, reaching 7.1305 Ci.

In Section 2, methodology and design goals are presented. Section 3 introduces the preliminary design of the LSSNR, followed by focused optimizations that result in a finalized core configuration. Section 4 presents the thermal-hydraulic feasibility verification

of the LSSNR. Some neutronic analysis was discussed in Section 5. Finally, some conclusions are summarized in Section 6.

2. Design Goals and Research Method

Due to the complex neutron spectrum and geometric configuration of the LSSNR, conventional two-step deterministic methods face several challenges, including the absence of a well-defined few-group energy structure, limited applicability of lattice codes, and reduced accuracy in core diffusion calculations. In this study, an open-source Monte Carlo neutron transport code OpenMC [30], developed by the Computational Reactor Physics Group at MIT, was employed for the neutronic and burnup analyses of the LSSNR. The nuclear data library and depletion chain used in the OpenMC calculations are based on the ENDF/B-VII.1 library [31]. The neutron library in HDF5 format contains incident neutron, photon, thermal scattering, and windowed multipole data. In OpenMC, the Doppler broadening technique based on the windowed multipole (WMP) method enables on-the-fly resonance cross-section broadening based on user-defined temperatures. In addition, a Python 3.11 API can be used to simplify the modeling of the complex reactor core geometry.

For space exploration, the design of space nuclear reactor mainly focuses on the minimization of the reactor core, long lifetime and high safety. The comparisons of different historical space reactors in terms of fuel enrichment, fissile material loading, core power, core mass and lifetime are listed in Table 1. Space reactors are generally characterized by high enrichment and a fast neutron spectrum, typically without moderators, in order to reduce system mass and complexity. The reactor core mass is strongly correlated with lifetime, thermal power, and fuel enrichment. For space reactors with lifetimes exceeding 10 years and thermal power above 500 kW, the core mass and fuel enrichment are typically greater than 250 kg and 80%, respectively. Due to launch constraints and deep-space mission requirements, space reactors must satisfy stringent design requirements for mass, power, and lifetime. High power and long lifetime represent key development trends in space nuclear reactors. In addition, high power density requires enhanced heat transfer capability, while the fast neutron spectrum weakens the Doppler effect, potentially affecting operational safety.

Table 1. Some parameters of traditional space nuclear reactor.

Space Reactor	Fuel Type (Enrichment: wt.%)	Fuel Mass (kg)	Thermal Power (kW)	Core Mass (kg)	Lifetime
SNAP-10A [17]	U-ZrH (10)	46.36	34	114	43 days
HP-STMCs [32]	UN (55/70/85)	311.1	1641	753.7	10 years
HOMER15/25 [10]	UN (97)	128	125	358	5 years
SAIRS [13]	UN (83.5)	145.8	407–487	423.74	5–7 years
MSR [33]	UN (33.1)	310.9	1200	1080	5 years
SMSR [16]	LiF-BeF ₂ -UF ₄ (70–5–25%, 97)	178.4	100–1.5 × 10 ⁷	222.9	-
8 kW molten-salt-type reactor [17]	UF ₄ - ⁷ LiF-BeF ₂ (40–46.5–13.5%, 97)	87.3	69.72	349.3	10 years
M ² SR-1 [20]	LiF-UF ₄ (65–35%, 97)	210	210	-	8 years

To address these challenges, this study proposes a conceptual design of the LSSNR, which combines the advantages of conventional solid-fuel space reactors and molten salt reactors. The solid fuel employs highly enriched U-235 to compensate for reactivity loss due to depletion, while the liquid fuel contains only a small fraction of fissile material and provides negative temperature and void reactivity coefficients through thermal expansion effects. In addition, cross-shaped spiral fuel is adopted to enhance heat transfer performance by promoting liquid fuel mixing.

Based on the above considerations, the design objectives of the LSSNR are clearly defined as follows:

- (1) To achieve a long operational lifetime of 30 effective full power years (EFPY) at a thermal power level of 1 MW;
- (2) To limit the active core mass to less than 200 kg, ensuring compliance with launch constraints;
- (3) To provide enhanced inherent safety through sufficiently negative temperature and void reactivity coefficients, compared with conventional space reactor cooling systems;
- (4) To ensure that the reactor remains subcritical under accident conditions, without the possibility of returning to criticality;
- (5) To improve heat transfer performance through advanced fuel geometry design, thereby reducing peak fuel temperature and enhancing thermal reliability.

To clearly illustrate the overall research framework, the design and analysis of the LSSNR were carried out following a systematic, step-by-step procedure. First, the fuel element configuration was established, including the selection of candidate solid fuel materials (UN, UO₂, UC) and the evaluation of their neutronic performance under different U-235 enrichments. Based on this analysis, UC was preliminarily selected considering its neutronic and thermal advantages. Subsequently, the liquid fuel composition (⁷LiF-based molten salt with UF₄) was defined to provide negative reactivity feedback through thermal expansion, while maintaining a low fissile fraction.

Next, the fuel element structural design was determined, including the cross-shaped spiral geometry, cladding thickness, and helium gap size. The cladding material selection was then evaluated based on neutron economy, thermal conductivity, and compatibility with molten salt under high-temperature conditions, leading to an optimized choice.

Following the fuel element design, the study proceeded to the assembly and core-level configuration, where a hexagonal lattice arrangement was adopted to achieve a compact structure. Key geometric parameters such as fuel pitch, core size, and reflector configuration were determined. The overall reactor core design was then established, including the number of fuel elements, axial reflector layout, helium plenum for fission gas collection, and mass constraints.

Subsequently, the reactivity control system was designed using control drums with B₄C absorbers. A parametric analysis of absorber thickness was performed to ensure sufficient shutdown margin while meeting the lifetime requirement. In parallel, fuel enrichment and burnup performance were optimized to satisfy the 30 EFPY operation target.

Based on the finalized core configuration, thermal-hydraulic simulations were first performed using COMSOL. A reduced-scale model was developed to investigate coolant flow characteristics, heat transfer performance, pressure drop, and temperature distribution. The coupling between the cross-shaped spiral fuel geometry and coolant flow was analyzed to verify the feasibility of heat removal and thermal performance.

After that, a comprehensive neutronic parameter analysis was conducted. Key parameters, including temperature reactivity coefficients, coolant void reactivity worth, and Doppler effect, were evaluated using full-core models to assess inherent safety characteristics and reactivity feedback mechanisms under both normal and accident conditions.

3. Concept Design of LSSNR and Result

3.1. Fuel Element Design

Fuel element is one of the fundamental components of LSSNR and affects the neutronics characteristics of reactor core. In LSSNR, high operating temperature and molten salt corrosion require fuel, cladding and other materials with high-temperature resistance, corrosion resistance, good heat transfer performance, and stable physical properties.

A cross-shaped spiral fuel element was employed in LSSNR, as shown in Figure 1a, and is used in the thermal-hydraulic feasibility analysis presented in Section 4. However, a torsion less cross-shaped spiral fuel element was employed, as shown in Figure 1b. This simplification is introduced because accurate modeling of the fully twisted geometry in OpenMC presents significant computational challenges. The previous neutronic studies on cross-shaped spiral fuel rods have demonstrated that the impact of torsion less cross-shaped spiral fuel rods on neutronic characteristics is negligible [34]. Therefore, this simplification is considered reasonable for neutronic analysis. Additionally, the curved surfaces of the cross-shaped spiral fuel are approximated by right-angled surfaces.

To achieve a compact configuration, the LSSNR core adopts a hexagonal arrangement. Figure 2 shows the design of the hexagonal fuel lattice cell, which consists of the fuel, cladding, and coolant. In the preliminary design, according to the design parameters of traditional space reactors [9,13,14,35], the pitch of the hexagonal fuel elements was selected as 1.7 cm, the maximum radial distance from the center of the cross-shaped spiral fuel is 1.65 cm, the blade thickness of the cross-shaped spiral fuel is 1 cm and the thickness of the fuel cladding is 0.1 cm. A layer of He gap stays between the fuel and the cladding for the thermal expansion. The material volume expansion coefficient β and the linear expansion coefficient α have the following approximate relationship $\beta = 3\alpha$, and β is defined as Equation (1) [12]. Where T is the temperature in K, V is the material volume in cm^3 , r indicates the radius, ΔT means the temperature change, and h is the axial height. In this study, based on the thermal-hydraulic results of the LSSNR, the maximum temperature variation from cold condition to hot condition in the reactor core was determined to be approximately 800 K, which was used to define the size of the He gap. The linear expansion coefficients of materials commonly used in space nuclear reactors, such as UN, UO_2 and UC, are 9.9×10^{-6} (290 K–1870 K), 12.83×10^{-6} (298 K–2273 K), and 12.8×10^{-6} (298 K–2000 K), respectively, and the corresponding radius changes are 0.00652 cm, 0.00845 cm, 0.00843 cm, respectively. Thus, the inner and outer He gap of 0.005 cm can meet the design requirements.

$$\beta = \frac{1}{V} \cdot \frac{dV}{dT} = \frac{\pi(r + \Delta r)^2 h - \pi r^2 h}{\pi r^2 h \cdot \Delta T} \Rightarrow \Delta r = \sqrt{\beta r^2 \cdot \Delta T + r^2} - r \quad (1)$$

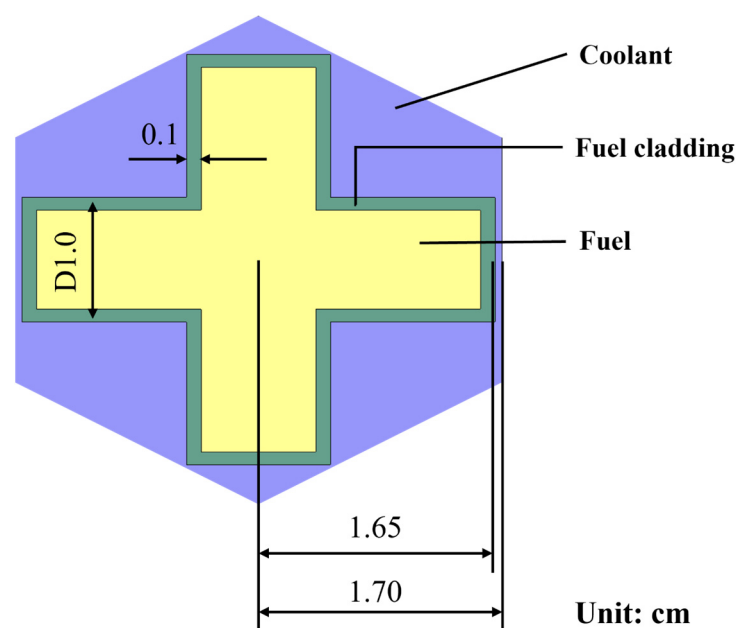


Figure 2. Schematic view of fuel element.

The LSSNR adopts a liquid-solid dual-fuel configuration, in which the solid fuel plays a dominant role in determining the neutronic characteristics. The effect of different solid fuel types and U-235 enrichments on k_{inf} of the fuel element was evaluated using the OpenMC code, as shown in Figure 3. Three fuel materials commonly used in space reactors, namely UN, UO_2 , and UC [36,37], were considered. The cladding material and molten salt are temporarily chosen as Mo-30Re and 7LiF - BeF_2 - UF_4 (49.55–49.55–0.9 mol%) with 30% U-235 enrichment as liquid fuel, respectively. In OpenMC calculation, 300 cycles with 500,000 neutron particles in each cycle were adopted and the first 100 cycles were ignored in result tally, and the boundary condition is reflective.

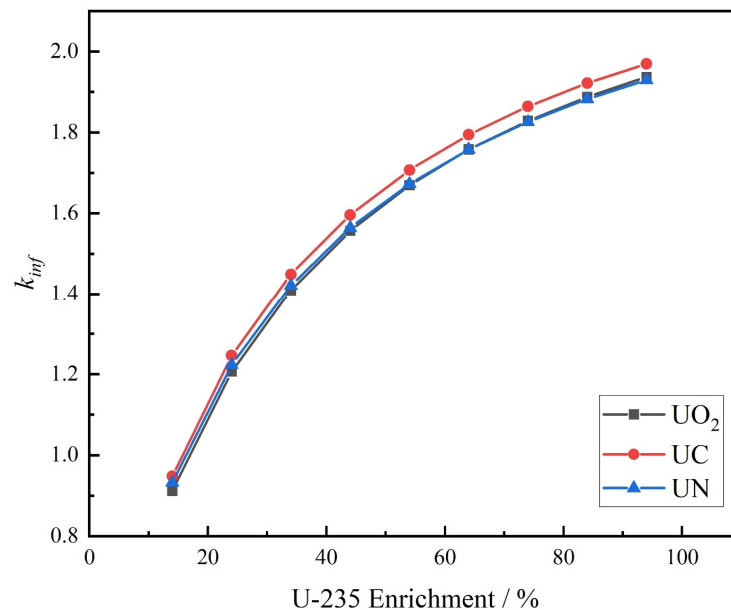


Figure 3. The variation in k_{inf} along enrichment for different kinds of fuel.

The results indicate that k_{inf} increases monotonically with U-235 enrichment for all fuel types. For the same enrichment, UC exhibits a slightly higher k_{inf} than UN and UO_2 , with an increase of approximately 2%, mainly due to the weak moderation effect of carbon. From an engineering perspective, carbide fuels offer significant advantages over oxide fuels due to their higher thermal conductivity. The thermal conductivity of UC ($18.8 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) is significantly higher than that of UO_2 ($2.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) and slightly higher than that of UN ($15.8 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), which helps reduce the peak fuel centerline temperature and enables higher linear power density and larger fuel dimensions. Although the density of UC (13.6 g/cm^3) is slightly lower than that of UN (14.31 g/cm^3), its overall thermal performance remains advantageous.

Despite its relatively higher swelling and fission gas release, UC is still considered a promising candidate fuel for space reactors [38]. These issues will be further discussed in Section 5.

Based on the above neutronic and thermal considerations, UC with 44% U-235 enrichment is preliminarily selected as the solid fuel for subsequent assembly-level parametric analysis. The enrichment level will be further optimized in future studies to meet the overall design requirements.

The selection of fuel cladding is another critical aspect of the LSSNR design. From the perspective of neutron economy, the cladding material should have low density and a low neutron absorption cross section. From the perspective of safety and thermal performance, it should exhibit good compatibility with molten salt, a high melting point, and high thermal conductivity.

To evaluate the impact of cladding materials on neutronic performance, several candidate materials commonly used in space reactors were analyzed, as summarized in Table 2 [39]. In OpenMC calculation, the two-dimensional fuel element model with reflective boundary condition and the UC solid fuel with 44% U-235 enrichment were employed.

Table 2. The physical parameters of cladding material and its k_{inf} .

Cladding	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Melting Point (K)	Density (g/cm^3)	k_{inf}
Ta alloys	-	3523	16.7	1.46871 ± 9.7 pcm
Nb alloys	41.9	2680	8.6	1.64792 ± 6.2 pcm
Zr alloys	21.2–32.6	2123	6.55	1.74645 ± 5.6 pcm
Ti alloys	6.7	1877–1933	4.43	1.74548 ± 5.4 pcm
Ni alloys	13.1–23.6	1300–1400	8.86	1.70921 ± 5.3 pcm
Mo-Re alloys	36.8	2723.15	11.963	1.59593 ± 6.9 pcm

The results indicate that tantalum (Ta) alloys possess a high melting point, which is advantageous for high-temperature operation; however, their relatively high density and neutron absorption cross section make them less favorable in terms of neutron economy. Titanium (Ti) alloys exhibit low density and good neutronic performance, but their thermal conductivity is lower than that of zirconium (Zr) and nickel (Ni) alloys.

Overall, the selection of cladding material requires a trade-off between neutronic performance and thermal-mechanical properties.

Since molten salt flows through the fuel channels, cladding compatibility with fuel salt must be considered. Studies have shown that increasing Mo content in Ni-based alloys can improve their resistance to molten salt corrosion [40], and such alloys are commonly used in molten salt reactors. Therefore, Ni-based alloy is adopted as cladding materials of the fuel element, respectively.

Three categories of fuel salt are generally used: (a) alkali-fluorides (e.g., ${}^7\text{LiF-KF}$, ${}^7\text{LiF-NaK-KF}$), (b) fluorides salt containing ZrF_4 (e.g., ${}^7\text{LiF-ZrF}_4$, NaF-ZrF_4), and (c) fluorides salts containing BeF_2 (e.g., ${}^7\text{LiF-BeF}_2$, NaF-BeF_2). According to the previous studies [41], the viscosity of alkali-fluorides is less than that of molten salt containing ZrF_4 and BeF_2 , and the viscosity increases with the increase in the molar ratio of BeF_2 to ZrF_4 . LSSNR chooses ${}^7\text{LiF-KF-UF}_4$ (49.55–49.55–0.9 mol%) with 30% U-235 enrichment as liquid fuel.

3.2. LSSNR Core Preliminary Design

The height to diameter (H/D) ratio of reactor active core is usually greater than 1, which can increase the reactivity worth of the control drum, shorten the heat transfer path, and increase the heat transfer area [42]. In order to achieve the design goal of compactness and core mass of less than 200 kg, LSSNR adopts a hexagonal layout with an active core pitch of 27.5 cm. The reactor core contains 61 fuel elements, and a 5 cm-high helium gap is arranged at the bottom of fuel element to collect the fission gas released during operation, the helium gap of the fuel rod is initially filled with helium at a pressure of 0.1 MPa under room temperature conditions. At both ends of the solid fuel, there are two 0.1 cm thick Re layers, which serve as a spectrally absorbing material. Reflectors with a height of 6 cm and 7 cm are respectively set in the bottom and top of active core, as shown in Figure 4.

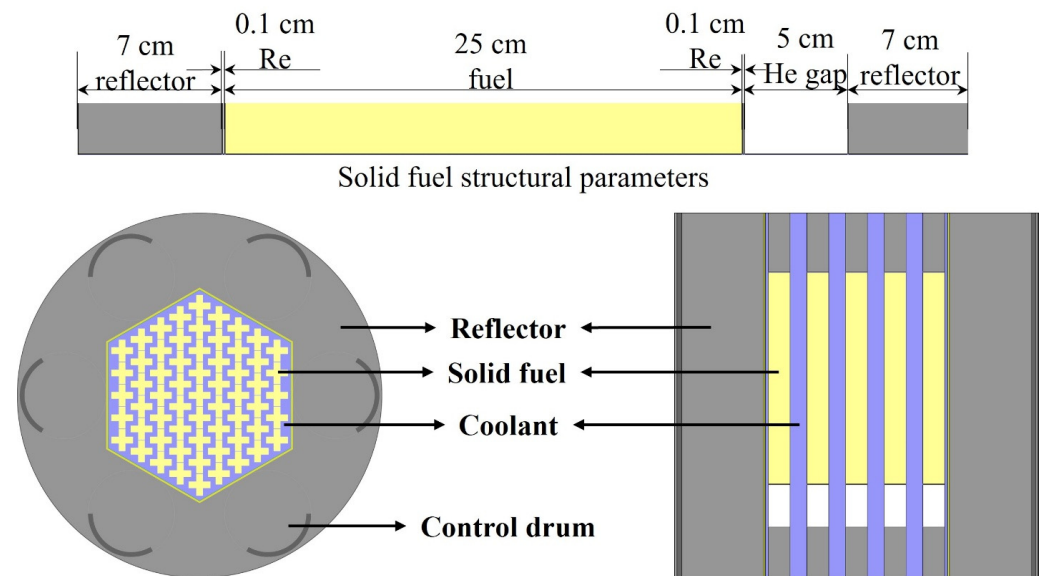


Figure 4. Radial and axial configuration of LSSNR.

To avoid the issue of robustness reduction caused by complex mechanical structure, control drums were used to control the core reactivity, maintain a subcritical state before entering orbit, and shut down the reactor after the mission is completed. As shown in Figure 4, LSSNR was configured by six control drums, and each has B_4C (B-10, 78.439 wt.%) coating with an opening angle of 120 degrees. Thus, the core reactivity can be adjusted by rotating the control drum and changing the B_4C position. The reflector can effectively reduce neutron leakage and improve neutron utilization. Space reactors typically operate at high temperatures, requiring reflector materials with both high scattering cross sections and excellent thermal resistance. Commonly used materials include BeO , Be , and Zr_3Si_2 . Additionally, U-235 enrichment of 80.283 wt.% was adopted to meet the 30 EFPY design target by OpenMC calculation. In this study, the reactor core k_{eff} (s) with different reflector was calculated based on the core model shown in Figure 4. Calculations with 300 cycles, 100 skipped cycles, and 1,000,000 neutron particles in each cycle were performed in OpenMC, and the boundary condition is vacuum. The physical parameters of reflector materials and reactor core k_{eff} are listed in Table 3. By comparison, core with BeO reflector shows a better k_{eff} and it has a higher melting point, while Zr_3Si_2 has a higher density and poorer neutron economy. Additionally, although Be has poor oxidation resistance at high temperatures, BeO overcomes this limitation and offers good thermal conductivity along with a low thermal expansion coefficient. Therefore, BeO was adopted as reflector and matrix material of control drum.

Table 3. Reactor core k_{eff} for different reflectors.

Reflectors	Be	BeO	Zr_3Si_2
Density (g/cm^3)	1.85	3.01	5.88
Melting point (K)	1556	2781	2580
Reactor core k_{eff}	1.06650 ± 8.6 pcm	1.07302 ± 8.1 pcm	0.938524 ± 9 pcm

LSSNR may re-enter the atmosphere and fall back to Earth in a launch accident. Subcritical LSSNR surrounded by sea water or wet sand has a possibility of returning to criticality since the isotope of H in water or Si in sand will soften the neutron spectrum. To avoid this, a spectral shift absorber (SSA) was adopted in LSSNR, which has a smaller absorption cross section for fast neutrons and is the opposite for thermal neutrons, as shown in Figure 5. In LSSNR, a layer of SSA with 0.02 cm thickness was added to the

outer of cladding. SSAs including B_4C , $^{149}Sm_2O_3$, Eu_2O_3 , Gd_2O_3 and Rhenium are usually employed in space reactors, and the physical parameters are listed in Table 4, where B_4C , Eu_2O_3 , and Gd_2O_3 are enriched with natural elements. In this study, the reactivity penalties caused by different SSA materials were studied for three cases based on the preliminary LSSNR design: (1) initial core configuration (Figure 4), (2) bare reactor core (no outer reflector) with vacuum boundary condition, and (3) bare reactor core surrounded by wet sand. The wet sand of density 2.16 g/cm^3 consists of 85.8 wt.% SiO_2 and 14.2 wt.% sea water, and sea water consists of 96.9 wt.% H_2O and 3.1 wt.% $NaCl$.

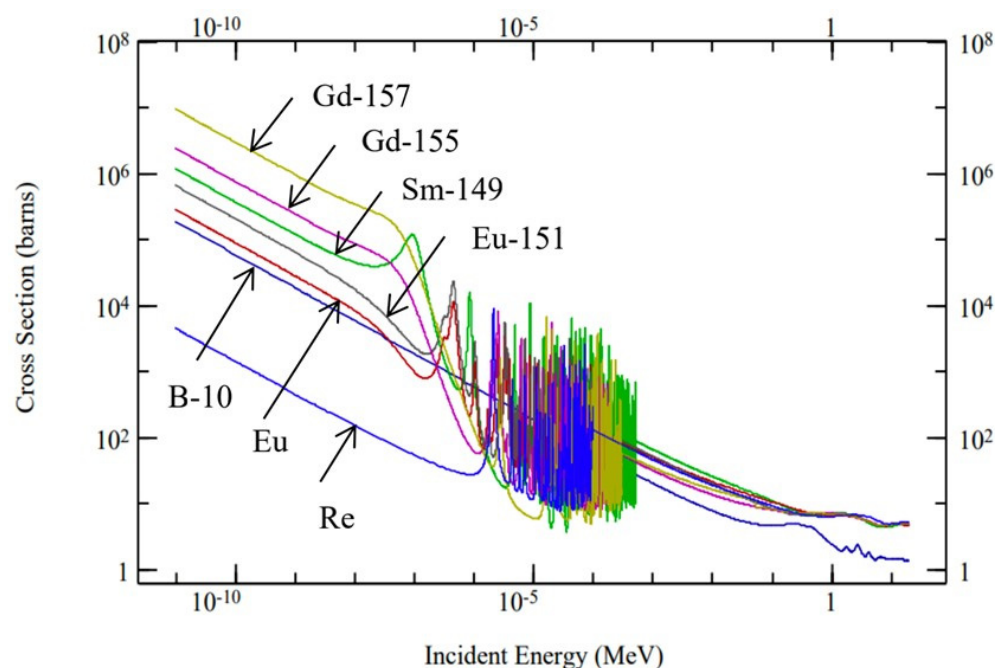


Figure 5. The absorption cross section of potential nuclide used as SSA.

Table 4. The physical parameters for SSA [43].

SSA	Melting Point (K)	Density (g/cm^3)
B_4C , $^{10}B_4C$	2623	2.52
$^{149}Sm_2O_3$	2542	7.60
Eu_2O_3 , $^{151}Eu_2O_3$	2564	7.42
Gd_2O_3 , $^{155}Gd_2O_3$, $^{157}Gd_2O_3$	2612	7.07
Rhenium	3441	21.02

The results are summarized in Table 5. It can be seen that Gd_2O_3 SSA causes the least reactivity penalty for case 1. For reactor core surrounded by wet sand (case 3), the original LSSNR core without any SSAs still remains supercritical. Thus, adopting SSA material in LSSNR is necessary. However, Rhenium has the weakest spectral shift absorption ability, and $^{10}B_4C$ caused the greatest reactivity penalty. B_4C , commonly used as a control material in PWR, has a relatively large absorption cross-section, especially for thermal neutrons, but it was not directly used as fuel cladding in space nuclear reactors. Compared with Sm-149, Gd provides better neutron economy and a significantly smaller reactivity penalty, which is beneficial for achieving the long lifetime design objective. Overall, Gd_2O_3 was adopted in LSSNR.

Table 5. Reactor core k_{eff} for different SSA.

Case	1	2	3
Zr (original)	1.09653 ± 8.4 pcm	0.783770 ± 9.7 pcm	1.05225 ± 9.0 pcm
B ₄ C	1.06120 ± 7.3 pcm	0.780991 ± 9.3 pcm	0.961193 ± 10 pcm
¹⁰ B ₄ C	0.973006 ± 8.5 pcm	0.748909 ± 9.6 pcm	0.879403 ± 10 pcm
¹⁴⁹ Sm ₂ O ₃	1.06215 ± 8.0 pcm	0.781216 ± 10 pcm	0.950383 ± 10 pcm
Eu ₂ O ₃	1.05235 ± 8.2 pcm	0.775967 ± 10 pcm	0.951283 ± 10 pcm
¹⁵¹ Eu ₂ O ₃	1.04799 ± 7.9 pcm	0.776853 ± 10 pcm	0.943306 ± 10 pcm
Gd ₂ O ₃	1.07859 ± 8.3 pcm	0.782756 ± 9.8 pcm	0.967662 ± 9.9 pcm
¹⁵⁵ Gd ₂ O ₃	1.06452 ± 9.0 pcm	0.779591 ± 9.3 pcm	0.955798 ± 9.9 pcm
¹⁵⁷ Gd ₂ O ₃	1.07269 ± 8.0 pcm	0.782602 ± 9.3 pcm	0.960294 ± 10 pcm
Rhenium	1.07192 ± 7.9 pcm	0.783612 ± 10 pcm	1.02219 ± 9.5 pcm

3.3. Control Drum Absorber Thicknesses Design

To satisfy the design requirement of a 30 EFPY lifetime while maintaining a sufficient shutdown margin—defined as the reactivity difference between the fully subcritical and critical states under the most unfavorable conditions—the thickness of the B₄C coating in the control drums was optimized. The variations in k_{eff} for absorber thickness ranging from 0.75 cm to 2.0 cm were calculated. Calculations with 300 cycles, 100 skipped cycles, and 1,000,000 neutron particles in each cycle were performed in OpenMC, and the boundary condition was set to vacuum.

To meet 30 EFPY operation, the U-235 enrichment was adjusted simultaneously, and the results are listed in Table 6. It shows that as B₄C coating thickness increases, the required U-235 enrichment increases, and the worth of the control drum also increases. Overall, solid fuel U-235 enrichment of 80.98 wt.% and B₄C thickness of 0.75 cm were adopted in LSSNR, and the variation in k_{eff} with operation time is drawn in Figure 6. In this configuration, k_{eff} of the LSSNR with the control drums in the fully inserted position is 0.954949, ensuring sufficient subcriticality. After 30 EFPY operation, the k_{eff} reaches 1.00592, which meets the requirement of operation life.

Table 6. k_{eff} and enrichment at different absorber thickness.

Thickness (cm)	Enrichment (wt.%)	k_{eff} When Absorber Is Closest to the Active Core	k_{eff} When Absorber Is Farthest to the Active Core
0.75	80.98	0.954949 ± 9.0 pcm	1.08644 ± 7.9 pcm
0.90	81.48	0.951129 ± 9.3 pcm	1.08841 ± 8.2 pcm
1.30	82.38	0.944649 ± 9.6 pcm	1.09192 ± 8.7 pcm
1.70	82.98	0.941185 ± 8.6 pcm	1.09356 ± 7.9 pcm
2.00	83.30	0.939626 ± 9.8 pcm	1.09398 ± 8.8 pcm

After launch, with all the control drum absorbers positioned closest to the active core, the control drums will be adjusted to make the reactor core critical. However, in some cases, the reactor core needs to be shut down by adjusting the absorber location. Reactivity margin in cases when one or more control drums are stuck needs to be analyzed. For control drum with 0.75 cm B₄C thickness, each control drum reactivity worth is 2192 pcm. During startup from subcriticality, the reactor core cannot reach criticality if five or more control drums are stuck. Conversely, the reactor core cannot shut down if three or more control drums are stuck (k_{eff} changes from 1.08644 to 1.02068 for 3 stuck control drums working).

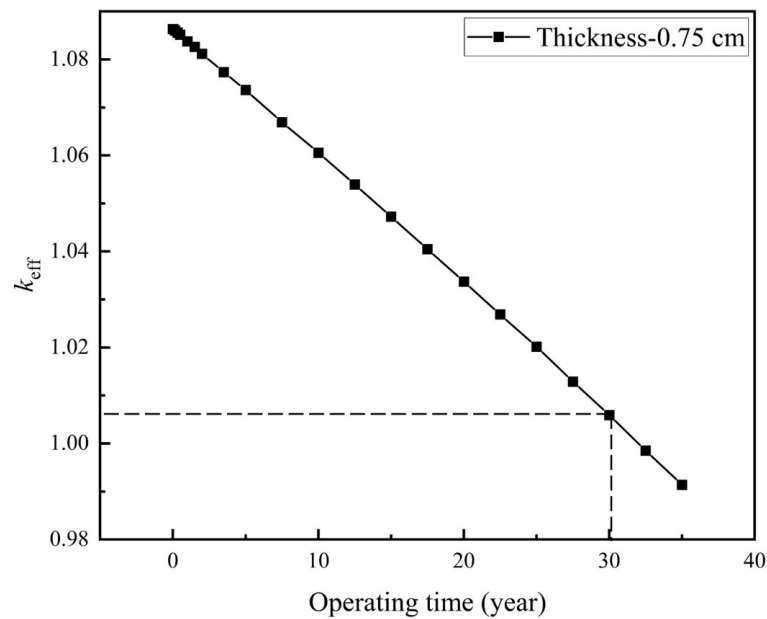


Figure 6. Variation in k_{eff} with operation time at 0.75 cm of thickness.

The physical and design parameters of optimized LSSNR are listed in Tables 7 and 8. The total mass of the active core is almost the same as the initial design scheme.

Table 7. Summary of LSSNR composition and characteristics.

	Type	Material	Density (g/cm ³)	Mass (kg)
Elements (61)	Coolant (1000 K)	⁷ LiF-KF-UF ₄	2.04735	23.65
	Fuel	UC	13.63	111.99
	Cladding	Ni alloys	8.86	6.13
	SSA	Gd ₂ O ₃	7.07	2.83
	Re	Re	21.02	2.04
	Axial Reflector	BeO	2.855	11.47
	Gap	He	-	-
Total mass of active core				158.11
Reactor	Active core cladding	Ni alloys	8.86	3.66
	Insulation material	APA-1	0.200	0.21
	Radial reflector	BeO	2.855	200.91
	Absorber	B ₄ C (B-10 100 wt.%)	2.510	6.31
Total				371.73

Table 8. Operating parameters for the LSSNR.

Operating Parameter	Value
Total power	1000 kW
Lifetime	~30 y
Void reactivity coefficient	−9426 pcm
Temperature reactivity coefficient	−2.362 pcm/K
Core temperature	1000 K
Enrichment of UC	80.98 wt.% U-235
Number of fuel pins	61
Active core pitch	27.5 cm
Active core height	43.2 cm
B ₄ C thickness	0.75 cm
Radial reflector thickness	13.4 cm
Axial reflector thickness	7.0 cm and 6.0 cm

4. Thermal-Hydraulic Feasibility Analysis of the LSSNR

In this section, the thermal-hydraulic feasibility of the LSSNR was analyzed by Multi-physics software COMSOL. To reduce time for whole-core Computational Fluid Dynamics (CFD) calculations, a simplified model based on a 4/61 reactor core configuration, as illustrated in Figure 7, was employed. The numerical data at the position labeled “PA” in Figure 7 were used for the subsequent analysis.

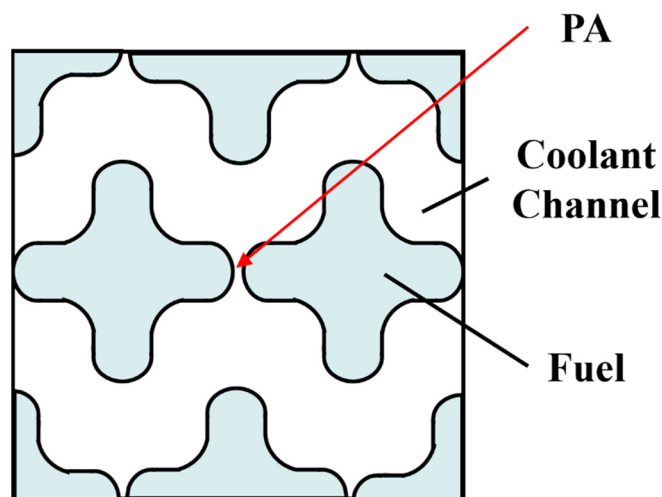


Figure 7. Schematic of the geometric model.

Different from neutronic calculation, no geometric simplifications were employed in thermal-hydraulic calculation. The rotation angle difference between the top surface and bottom surface of the cross-shaped spiral fuel rod is 360 degrees, that is, it rotates 30-degree angle for every 3.6 cm in height.

The fluid-solid coupled interface in COMSOL was employed to simulate the heat transfer between liquid and solid fuel. For the liquid fuel, an inlet velocity of 1 m/s and an inlet temperature of 873 K [40] were specified, and pressure was applied as the outlet boundary condition. The periodic boundary condition was respectively adopted for the fluid region and solid region in radial direction. The thermal power of the simulation model was set to 65 kW based on 1 MW of the whole core power. In LSSNR, both liquid fuel and solid fuel can generate fission heat. According to the neutronic calculation, the power ratio of solid to liquid, 2000:1, and uniform power density were employed in the thermal-hydraulic calculation. The $k-\varepsilon$ turbulence model based on the RANS approach was employed. To balance computational accuracy and efficiency, a mesh with 6.5 million elements was employed, yielding a grid quality of approximately 0.69. Verification results indicate that the mesh-induced error at this resolution is sufficiently small.

The thermal-hydraulic parameters of liquid fuel and solid fuel used in calculation are listed in Table 9. Nearly all the parameters were considered in relation to temperature. The unit of T in the table is K.

Table 9. The thermal-hydraulics parameters of liquid fuel and solid fuel.

Parameter	Liquid Fuel	Solid Fuel
Type	${}^7\text{LiF-KF-UF}_4$	UC
Density (kg/m)	2497.27–0.619·T	1363
Specific heat (J kg ^{−1} K ^{−1})	1947	1760
Thermal conductivity (W m ^{−1} K ^{−1})	0.93389	18.8 (1000 K)

4.1. Flow Characteristics

Transverse flow is a key parameter characterizing radial fluid disturbances. It can lead to a uniform temperature distribution of the coolant flow field within the fuel assembly, reduce local temperature peaks, and achieve enhanced heat transfer by generating turbulence. The transverse velocity is defined by Equation (2), where u_{tra} is the transverse velocity in m/s; u_x is the X-direction velocity in m/s; u_y is the Y-direction velocity in m/s.

$$u_{tra} = \sqrt{u_x^2 + u_y^2} \quad (2)$$

Figure 8 shows the transverse flow distribution at heights of 10.8 cm, 14.7 cm, 16.2 cm and 18.9 cm, which covers the first 90-degree rotation angle. The axial region corresponding to the second 90-degree rotation exhibited similar flow characteristics. Due to the cross-shaped spiral geometry of the solid fuel rods in the LSSNR, significant transverse flow was observed in the coolant channels. This transverse flow was primarily concentrated around the elbow regions of the blades of the cross-shaped spiral fuel rods. In contrast, the transverse flow at the blade tips was relatively weak. Additionally, the transverse velocity of the coolant flow field at the center of the channel is also low, as this region is distant from the rod bundle. The turbulent kinetic energy generated by the cyclonic flow dissipates before reaching the central region of the channel.

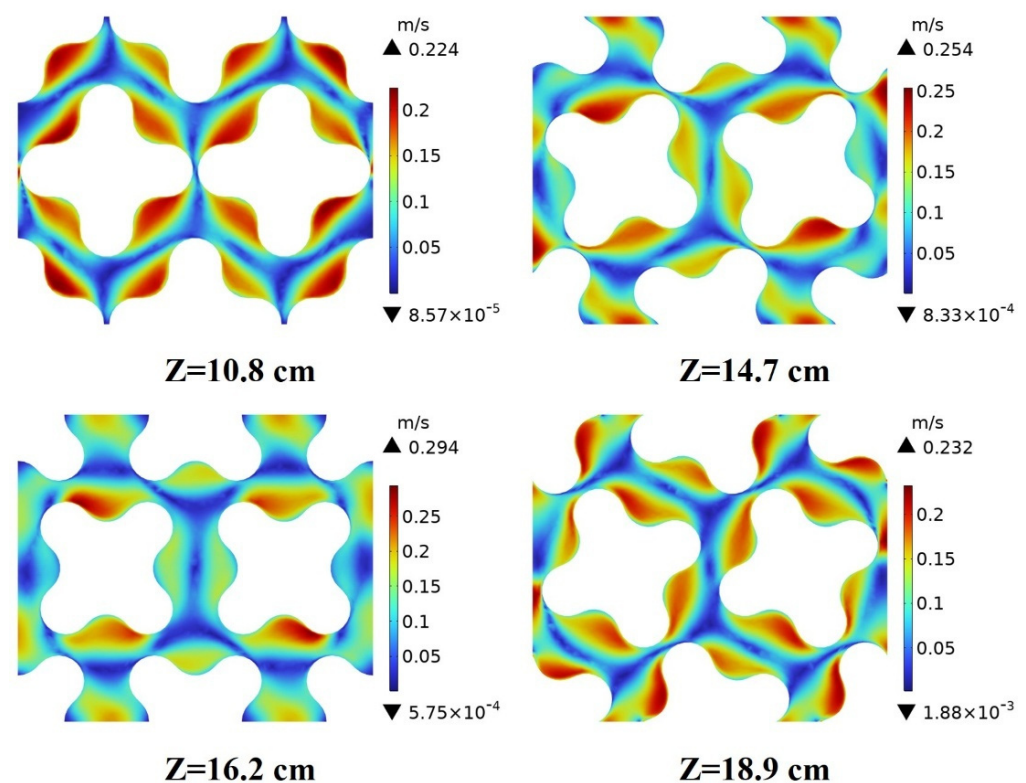


Figure 8. Schematic diagram of the intensity of the cross-currents.

The twisted structure of the cross-shaped spiral fuel element enhances the transverse flow. Turbulent kinetic energy was also used to quantitatively study the movement characteristics of the liquid fuel, as shown in Equation (3), where k is the turbulent kinetic energy in m^2/s^2 , U is the mean velocity in m/s, and I is the turbulence intensity, which is a dimensionless parameter, usually defined as a statistical property of turbulent velocity fluctuations, specifically, the ratio of the standard deviation of the turbulent velocity to

the mean flow velocity. Turbulence intensity can be used to measure the chaotic nature of fluid flow.

$$k = \frac{3}{2}(UI)^2 \quad (3)$$

The turbulent kinetic energy along the axial direction at PA for LSSNR was shown in Figure 9. It presents 90-degree cycle characteristics for LSSNR (90-degree rotation for every 10.8 cm). The complex structure of the cross-shaped spiral fuel results in the drag of the fluid at the same location varying periodically with the structure.

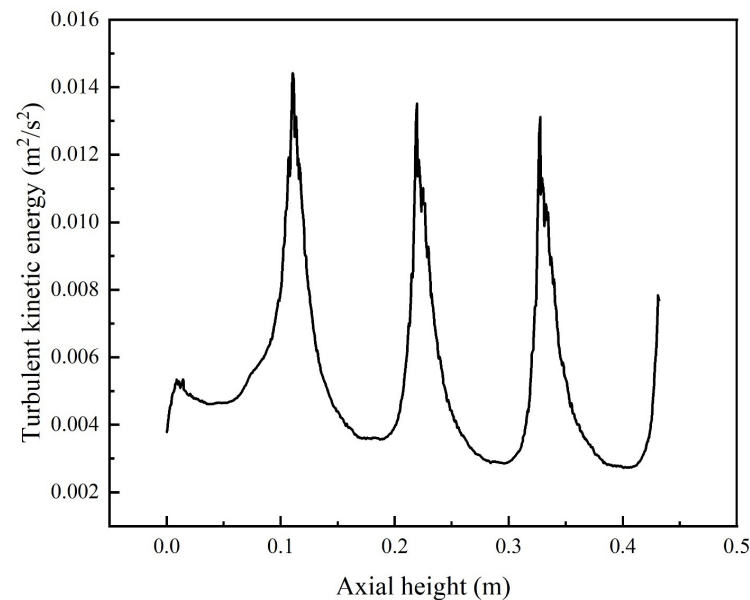


Figure 9. Turbulent kinetic energy at PA of LSSNR.

The pressure drop of the LSSNR from the inlet to the outlet was 9387.4 Pa. Figure 10 shows the relative pressure radial distribution at different heights of 14.7 cm, 16.2 cm and 18.9 cm, corresponding to rotation angles of 22.5, 45 and 67.5 degrees. The peak pressure was observed in the inner elbow region on the windward side of the cross-shaped spiral fuel, while the pressure on the leeward side was relatively lower. The complex geometry of the cross-shaped spiral fuel increased flow resistance and enhanced lateral disturbance, resulting in a non-uniform radial distribution of thermal-hydraulic parameters.

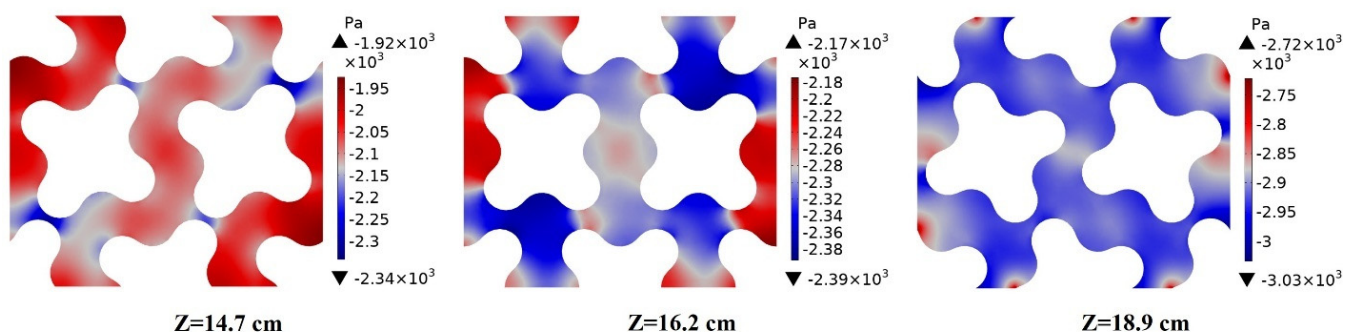


Figure 10. Schematic diagram of relative pressure distribution.

4.2. Heat Characteristics Analysis

Figure 11 shows the axial distribution of fuel rod central temperature and coolant temperature at PA. The fuel rod central temperature rises slowly after axial height 0.05 m. The maximum temperature of the fuel rod center is 1075 K, and the minimum temperature is 873 K. The coolant (liquid fuel) temperature exhibited a gradual increase in the inlet

region and began to rise more significantly after an axial height of 0.1 m. A periodic variation was observed, with a maximum temperature difference of approximately 12 K.

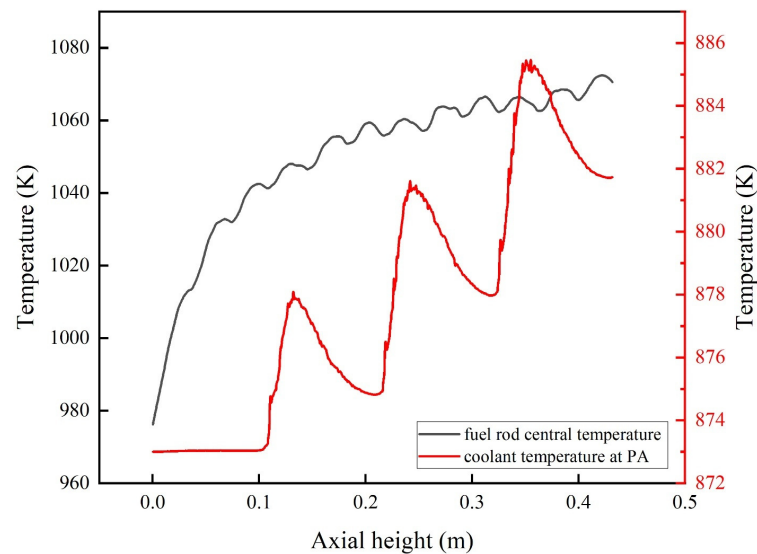


Figure 11. The axial distribution of fuel rod central temperature and coolant temperature at PA.

This behavior is attributed to the enhanced heat transfer induced by the cross-shaped spiral fuel elements. The torsional geometry of the fuel rod periodically changes the coolant flow area, generating flow disturbance and turbulence. As a result, the coolant temperature exhibited alternating increases and decreases along the axial direction, while the overall trend remained increasing in the flow direction.

Overall, the cross-shaped spiral fuel, due to its unique structure, induces a more pronounced transverse churn in the coolant flow within the channel, thereby enhancing heat transfer and improving the removal of heat from the fuel rods. The thermal-hydraulic behavior of the LSSNR has been demonstrated to be feasible.

5. Neutronics Analysis of LSSNR

Based on the above LSSNR preliminary design scheme, some neutronic characteristics were analyzed including reactivity coefficients, criticality safety in a launch accident, fission gas and core radioactivity

5.1. Reactivity Coefficients

Reactivity coefficients play an important role in core safety. LSSNR has solid fuel and molten salt fuel at the same time; thus, two types of fuel temperature reactivity coefficients were calculated. It should be noted that the volume of solid fuel is hardly changed in temperature variation. However, the change in molten salt fuel density must be considered in the calculation of fuel temperature reactivity coefficient. The relationship between molten salt fuel density and temperature is shown in Equation (4) [44]. Where ρ means the density of molten salt fuel (g/cm^3), T indicates the molten salt fuel temperature ($^{\circ}\text{C}$).

$$\rho = 2.49727 - 0.000619 \cdot T \quad (4)$$

Due to the hard neutron spectrum in LSSNR, the Doppler effect is relatively weak. OpenMC calculation adopted 2000 cycles, 800 skipped cycles and 1,500,000 particles per cycle, and the k_{eff} standard deviation is less than 1.9 pcm. The temperature reactivity coefficients were evaluated using the full-core model with vacuum boundary conditions, ensuring that the neutron leakage effect was inherently considered. Six temperature points

of interval 100 K in the range 600 K to 1100 K were used to calculate temperature reactivity coefficients. Three cases were performed: only changing solid fuel temperature, only changing temperature of molten salt fuel, and changing both temperatures. Moreover, the coolant void reactivity worth was calculated, where two conditions, including liquid fuel filling the core (0% void fraction) and complete emptying (100% void fraction), were adopted. The results are listed in Tables 10 and 11. The temperature reactivity coefficients of both the solid and liquid fuels are negative, indicating inherent negative feedback. The void reactivity worth is -9426 pcm. The Doppler effect is weak for fast neutron spectrum of LSSNR, and a large part of negative fuel temperature coefficient is provided by liquid fuel containing few U-235 due to its thermal expansion effects. That is, LSSNR has more a negative temperature coefficient compared to conventional solid-fuel space reactors (generally about -0.07 pcm/K).

Table 10. Temperature reactivity coefficient of LSSNR.

Case	Reactivity Coefficient (pcm/K)
Only change solid fuel temperature	-0.062
Only change molten salt fuel temperature	-2.362
Change both temperatures	-2.424

Table 11. Void reactivity worth of LSSNR.

Case	k_{eff}
0% void fraction	1.08644
100% void fraction	0.99213
Void worth	-9431 pcm

5.2. Criticality Safety in a Launch Accident

LSSNR may re-enter the atmosphere and fall back to Earth in a launch accident [42]. Subcritical LSSNR surrounded by sea water or wet sand has the possibility of returning to criticality since the isotope of H in water or Si in sand will soften the neutron spectrum. The previous research has studied criticality safety of space reactor under four conditions [43]. It should be noted that the space reactor remains subcritical before entering orbit, i.e., all the control drums rotate inward (the absorbers are closest to the active core). Thus, criticality safety in three extreme cases was analyzed: (1) bare core without reflector at vacuum boundary condition, (2) cold reactor core surrounded by water or wet sand, (3) cold bare core surrounded by water or wet sand. The results listed in Table 12 show that positive reactivity is introduced in any case of launch accident, but LSSNR still remains subcritical. More positive reactivity is introduced for the core surrounded by wet sand than that surrounded by sea water.

Table 12. Core k_{eff} at different launch accidents.

Case	Reflector	Boundary	Absorber	k_{eff}
1	No	Vacuum	No	0.844324 ± 6.2 pcm
2	Yes	Sea water	Closest to core	0.985892 ± 7.6 pcm
	Yes	Wet sand	Closest to core	0.989052 ± 8.2 pcm
3	No	Sea water	No	0.927433 ± 7.1 pcm
	No	Wet sand	No	0.985138 ± 6.9 pcm

5.3. Fission Gas and Core Radioactivity Analysis

Fission gas will be generated in both solid fuel and molten salt fuel for LSSNR. Fission gas produced in solid fuel will be collected in He gap and restricted by cladding, while fission gas generated in molten salt fuel will cycle throughout the primary loop. The pressure of He gap will rise due to fission gas gathering, which affects cladding integrity and reactor safety. Furthermore, the effects of fission products and radionuclides from neutron activation should be analyzed in LSSNR design. The fraction of fission products released from solid fuel to He gap is represented by Release to Birth Ratio (R/B). The diffusion of fission products in UC fuel follows Fick's law, and R/B is closely related to fuel temperature and burnup level. UC fuel has a similar diffusion coefficient with UO_2 fuel, and its UC R/B is about 40% when the burnup level is $70 \text{ MW}\cdot\text{d}\cdot\text{kg}^{-1}$ at the end of operation time. This value was used as the most extreme calculation.

In the calculation, the isotopes Kr-80, Kr-83, Kr-84, Kr-85, Kr-86, Xe-126, Xe-128, Xe-129, Xe-130, Xe-131, Xe-132, Xe-133, Xe-134, Xe-135 and Xe-136 were considered. At the end of 30 EFPY, the pressure created by fission gas was calculated by ideal gas equation of state. The LSSNR includes five radial fuel rod regions, labeled R1 through R5 from the center outward. Table 13 shows the pressure of fission gas at the end of operation time for different regions. The effect of fuel irradiation swelling and creep on He gap volume is not considered. The pressure of fission gas of inner fuel region is 5.538 MPa, which is relatively larger than that of outer fuel region due to deeper burnup level. In LSSNR solid fuel element, the cladding material is Ni-based alloy. According to the previous studies [45], this cladding material can withstand pressures in excess of 7 MPa after accounting for neutron irradiation and other relevant factors.

Table 13. Pressure of fission gas at the end of operation time for different regions.

Region	Amount of Substance (mol)	He Gap Volume (cm^3)	Pressure (MPa)
R1	0.08021	36.122	5.538
R2	0.08040	36.898	5.435
R3	0.08027	39.072	5.124
R4	0.08062	41.443	4.852
R5	0.07924	41.443	4.769

The radioactivity of solid fuel and molten salt fuel after 30 EFPY were calculated, as shown in Table 14 and Figure 12. Actinides in LSSNR have small radioactivity. In the first 10 years after the end of core life, radioactivity decreases from $1.1639 \times 10^3 \text{ Ci}$ to $1.1405 \times 10^3 \text{ Ci}$. Apart from actinides, radioactivity mainly comes from isotopes Sr-89 (half-life 50.532 days), Sr-90 (half-life 28.9 years), Y-90 (half-life 2.662 years), and Cs-137 (half-life 30.08 years). After 100 years of the end of core life, the total radioactivity of reactor core is reduced by 99% and is 7.1305 Ci. After 300 years of the end of reactor core life, 90% radioactivity comes from actinides, where Pu-238 (half-life 87.84 years), Pu-239 (half-life 2.411×10^4 years) and Pu-240 (half-life 6.561×10^3 years) is 64.57%.

Table 14. Radioactivity of solid fuel and molten salt fuel after 30 EFPY operation.

Time (Year)	UC Radioactivity (Ci)	Liquid Fuel Radioactivity (Ci)	Total Radioactivity (Ci)
0	1.1629×10^3	2.7733×10^{-1}	1.1632×10^3
0.01	6.8497×10^2	1.2618×10^{-1}	6.8509×10^2
1	1.1405×10^2	1.8671×10^{-2}	1.1407×10^2
100	7.1293×10^0	1.1550×10^{-3}	7.1305×10^0
300	2.3082×10^{-1}	7.8626×10^{-5}	2.3090×10^{-1}

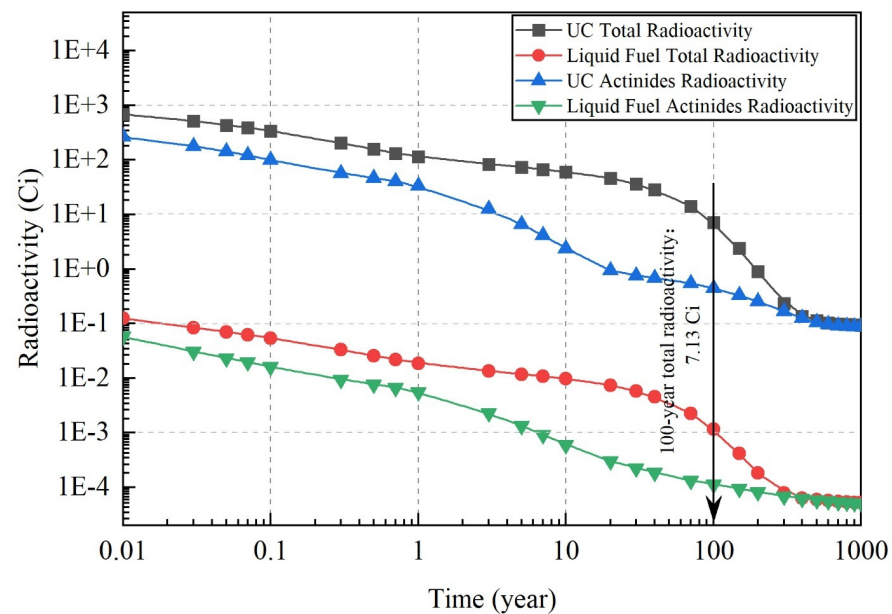


Figure 12. Radioactivity variation along time after 30 EFY operation.

6. Conclusions

In this study, a novel liquid-solid dual-fuel space nuclear reactor (LSSNR) was preliminarily proposed, combining the advantages of molten salt fuel and solid fuel to achieve enhanced performance and safety. The LSSNR adopts a hexagonal core layout with an active core pitch of 27.5 cm and consists of 61 fuel assemblies. A 5 cm-high He gap is arranged at the bottom of each fuel assembly to accommodate fission gas release, while axial reflectors with heights of 6 cm and 7 cm are placed at the bottom and top of the core, respectively. The molten salt fuel is ${}^7\text{LiF-KF-UF}_4$ (49.55–49.55–0.9 mol%) with 30% U-235 enrichment, while UC is selected as the solid fuel. In addition, Gd_2O_3 is employed as a secondary safety absorber (SSA) to enhance safety under potential launch accident conditions. Neutronic optimization indicates that a configuration with 80.98 wt.% U-235 enrichment in the solid fuel and a B_4C absorber thickness of 0.75 cm provides a sufficient shutdown margin while satisfying the 30 EFY lifetime requirement. In this optimized design, k_{eff} is 0.954949 with the control drums in the fully inserted position, ensuring subcriticality. After 30 EFY of operation, k_{eff} increases to 1.00592, meeting the requirement for sustained critical operation over the reactor lifetime. The total mass of the active core is 158.11 kg, which satisfies the design target of less than 200 kg. Thermal-hydraulic analysis demonstrates that the cross-shaped spiral fuel enhances transverse mixing within the coolant channel, leading to improved heat transfer and effective heat removal from the fuel. The coolant flow characteristics are well matched to the reactor power, confirming the thermal-hydraulic feasibility of the design. In addition, safety-related characteristics, including reactivity coefficients, criticality under potential launch accident conditions, fission gas behavior, and core radioactivity, were systematically evaluated. The results show that the LSSNR exhibits strongly negative reactivity coefficients and that the pressure induced by fission gas release remains within acceptable safety limits.

Overall, the proposed LSSNR design achieves the targeted goals of long lifetime, compact core size, and enhanced safety. However, further work is required to address challenges associated with scaling the reactor for higher power applications and extended mission scenarios.

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writing—review and editing, Z.Q.; visualization, D.L.; supervision, S.W. and J.C.; project administration, K.Z.; funding acquisition, K.Z. All authors have read and agreed to the published version of the manuscript.

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