Neutronics Design and Analysis of a Novel Liquid-Solid Space Nuclear Reactor Based on Cross-shaped Spiral Fuel

Authors: Qiu, Mr. Zhichao, Zhuang, Dr. Kun, Wang, Xiaoyu, Gao, Mr. Yong, Cao, Mr. Yun, Liu, Mr. Daping, Chen, Dr. Jingen (Nuclear energy), Wang, Sipeng, Dr. Kun Zhuang

Date: 2025-06-05T21:26:23+00:00

Abstract

As the key technology of space exploration, space power has always been a research interest of international researchers. A lot of research work has been carried out around the world for the space nuclear reactor using heat pipe, liquid metal and gas cooling method. With the development of molten salt reactor of IV generation 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 reactor. In this study, a novel reactor Liquid-Solid Dual-Fuel Space Nuclear Reactor (LSSNR) was preliminarily proposed combining the molten salt fuel and cross-shaped spiral solid fuel for the design goals of 30-year lifetime and active core weight less than 200 kg. Monte Carlo neutron transport code OpenMC based on ENDF/B-VII.1 library was employed for neutronics design in aspect of fuel type, cladding material, reflector material and spectral shift absorber. Then, the thickness of control drum absorber was optimized to meet the requirement of the sufficient shutdown margin, lower solid fuel enrichment, and 30 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 reflector and matrix material of control drum. A spectral shift absorber Gd2O3 was used to avoid the sub-critical LSSNR returning to criticality at a launch accident. The keff with control drum rotating innermost position is 0.954949, and the keff reaches 1.00592 after 30 EFPY operation. The total mass of the active core is 160.65 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, leads to a uniform temperature distribution of the coolant flow field, and reduces local temperature peaks. Based on 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. After 100 years of the end of core life, the total radioactivity of reactor core is reduced by 99% and is 7.1305 Ci.

Full Text

Preamble

Neutronics Design and Analysis of a Novel Liquid-Solid Space Nuclear Reactor Based on Cross-shaped Spiral Fuel

Zhichao Qiu,[1] Kun Zhuang,[1],† Xiaoyu Wang,[1] Yong Gao,[1] Daping Liu,[1] Yun Cao,[1] Jingen Chen,[2] and Sipeng Wang[1]

[1]Department of Nuclear Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 211106, China

[2]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, 201800, China

As the key technology for space exploration, space power has always been a research focus for international researchers. Extensive research has been conducted worldwide on space nuclear reactors using heat pipe, liquid metal, and gas cooling methods. With the development of molten salt reactors as part of Generation IV reactor systems, the use of molten salt to dissolve fissile material while simultaneously serving as coolant has emerged as a novel cooling scheme, providing new ideas for space nuclear reactor design. In this study, a novel Liquid-Solid Dual-Fuel Space Nuclear Reactor (LSSNR) was preliminarily proposed, combining molten salt fuel with cross-shaped spiral solid fuel to meet design goals of a 30-year lifetime and an active core weight less than 200 kg. The Monte Carlo neutron transport code OpenMC, based on the ENDF/B-VII.1 library, was employed for neutronics design aspects including fuel type, cladding material, reflector material, and spectral shift absorber. The thickness of the control drum absorber was then optimized to meet requirements for 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 B_4C thickness of 0.75 cm were adopted in LSSNR, with BeO serving as both reflector and matrix material for the control drum. A spectral shift absorber Gd_2O_3 was used to prevent a sub-critical LSSNR from returning to criticality in a launch accident. The k_{eff} with the control drum in its innermost position is 0.954949, and k_{eff} reaches 1.00592 after 30 EFPY operation. The total mass of the active core is 160.65 kg. Additionally, 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, leading to uniform temperature distribution in the coolant flow field and reducing local tem-

perature peaks. Based on the LSSNR scheme, several neutronic characteristics were analyzed.

Results demonstrate that LSSNR has strongly negative reactivity coefficients due to thermal expansion of the liquid fuel, and the fission gas-induced pressure meets safety requirements. After 100 years following the end of core life, the total radioactivity of the reactor core is reduced by 99% to 7.1305 Ci.

Keywords: Space nuclear reactor, Molten salt, Neutronics, Dual-fuel, Cross-shaped spiral fuel, OpenMC

INTRODUCTION

Human space exploration activities are flourishing with advances in science and technology. As a key technology for space exploration, space power has always attracted research interest from international investigators [1]. The application of nuclear energy in space exploration has been extensively studied worldwide. Based on nuclear energy generation methods, space nuclear power is primarily divided into two categories. The first is Radioisotope Thermoelectric Generators (RTGs), which convert decay heat from radioisotopes such as ^{238}Pu and ^{241}Am into electrical energy through thermoelectric conversion devices. The second category is space nuclear reactor power, which converts fission energy from reactions between fissile materials and neutrons into electrical energy. Space nuclear reactor power can better meet the high-power requirements of deep space exploration and offers stronger competitiveness and greater development prospects compared to other energy forms. Three cooling methods are generally employed in space nuclear reactors: alkali metal (Na, K, Li) heat pipes, liquid metal (Na, NaK, Li), and gas (He-Xe mixed gas, CO_2).

Extensive research has been conducted globally on these three types of space nuclear reactors. The United States, Russia, Japan, Europe, and other nations have proposed dozens of design schemes for space nuclear reactors, some of which have achieved space deployment. In 1955, the United States Atomic Energy Commission designed SNAP-10A using UH-Zr fuel and NaK coolant, with a mass of 400 kg [2]. The United States proposed the SP-100 space nuclear reactor adopting UN ceramic fuel and liquid metal Li coolant [3]. Aiming to develop a simple system, Los Alamos National Laboratory carried out the HOMER program for a fission reactor based on heat pipes [4]. The TOPAZ space nuclear reactor with a super-thermal neutron energy spectrum, developed in the 1980s, adopts UO_2 fuel elements with 96% enrichment, ZrH moderator, and liquid NaK-78 coolant [5].

Several studies on advanced space reactors have begun worldwide in the new century. The Massachusetts Institute of Technology (MIT) proposed a Martian surface reactor employing UN with 33.1% enrichment as fuel, cooled by lithium heat pipes, with a thermal power of 1.2 MW [6]. Since 2004, the University of New Mexico has proposed conceptual designs for the SAIRS, HP-STMCs, SCoRe, and S^4 space nuclear reactors using traditional cooling methods [7, 8].

Based on the design concept of a prismatic high-temperature gas-cooled reactor, Tsinghua University proposed a lithium-cooled space reactor based on UN dispersed particles and studied its neutronics characteristics [9]. Xi'an Jiaotong University, the University of Science and Technology of China, and Harbin Engineering University have respectively studied heat-pipe, liquid metal, and He-Xe gas-cooled space reactors, performing analyses of neutronics, thermal-hydraulics, and safety features.

It can be seen that current space reactor designs generally adopt heat-pipe, liquid metal, and gas cooling to transfer fission heat. With the development of molten salt reactors as part of Generation IV reactor systems, the use of molten salt to dissolve fissile material while simultaneously acting as coolant has become a new cooling scheme, providing new ideas for space nuclear reactor design. In the 1950s, molten salt reactors developed in the American nuclear-powered aircraft ANP program were more competitive for deep space exploration due to their light weight, high reliability, and high operating temperature, and could be applied to propulsion and planetary surface power. Since then, scholars worldwide have conducted extensive research on molten salt space reactors. The NASA Steckler Space Grant project performed by Ohio State University demonstrated that molten salt space reactors have advantages in compactness, high power density, and high thermoelectric conversion efficiency. NASA proposed a program using molten salt reactor technology for nuclear power propulsion and studied advantages in power density, core volume, high-temperature operation, economy, and safety. The analysis results show that molten salt space reactors can meet all needs of deep space exploration and offer greater advantages in these aspects. Ohio State University proposed a preliminary design of a space molten salt reactor core based on a mixed molten salt fuel of LiF, BeF_2, and UF_4, using MCNPX for critical calculations and temperature reactivity coefficient calculations. The results show that due to thermal expansion of fluorine salt, the fuel temperature coefficient reached -0.016 $/K, and FLUENT was then used to analyze fuel stagnation [10]. Japan proposed a heat pipe molten salt space reactor based on UF_{4}–^{7}LiF–BeF_{2}–ZrF_{4} fuel and studied core temperature at the beginning and end of lifetime using a heat balance model [11]. In addition, neutron flux, reaction rate distribution, control module values, and startup transient characteristics were also analyzed.

To enhance heat transfer performance of space reactors and further increase their power density, research on novel cross-shaped spiral fuel has garnered significant attention in recent years. The European Fission Federation (EFF) has adopted cross-shaped spiral fuel rod designs, which arrange multiple fuel particles in a spiral structure to improve fuel utilization and energy output efficiency. Using new oxide dispersion strengthened (ODS) material as fuel rod cladding provides better resistance to high temperatures and radiation, reducing risks from thermal expansion and cracking. Qi Zhang et al. [12] compared thermo-hydraulic properties of helical cross-shaped fuel with wire-packed fuel and found that the Nusselt number and friction factor of helical cross-shaped fuel increased by 4.6% compared to linear fuel. T.M. Conboy et al. [13] evaluated helical cross assemblies for high-power light-water reactors and showed that a boiling-water reactor with helical cross fuel allowed a 24% increase in power for a helical cross fueled core with 200 cm of torque compared to conventional fuel. Yuliang Fang et al. [14] found that the helical cross design enhances radial heat transfer and can generate strong rotational flow near the wall of the interfering boundary layer, which reduces the hot spot factor.

Space reactor research primarily focuses on long life, miniaturization, and safety. This study proposes the conceptual design of a Liquid-Solid Dual-Fuel Space Nuclear Reactor (LSSNR), which combines advantages of conventional solid-fuel space reactors and molten salt reactors while incorporating cross-shaped spiral fuel with enhanced heat transfer performance. First, part of the fission energy is directly released into the molten salt, which can effectively reduce solid fuel centerline temperature and increase output temperature, benefiting high-power density and high thermoelectric conversion efficiency designs. Second, due to thermal expansion and contraction effects of molten salt fuels, LSSNR exhibits more negative temperature and void reactivity coefficients, improving inherent safety. Third, compared with pure liquid fuel molten salt reactors, most fission products of LSSNR are sealed in solid fuel, greatly reducing the content and radioactivity of fission products in the liquid fuel.

In this study, a novel Liquid-Solid Dual-Fuel Space Nuclear Reactor (LSSNR) was preliminarily proposed, combining molten salt fuel and cross-shaped spiral solid fuel for design goals of 30-year lifetime and active core weight less than 200 kg. The Monte Carlo neutron transport code OpenMC based on the ENDF/B-VII.1 library was employed for neutronics design aspects including fuel type, cladding material, reflector material, and spectral shift absorber. The thickness of the control drum absorber was then optimized to meet requirements for 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 $B_{4}C$ thickness of 0.75 cm were adopted in LSSNR, with BeO serving as reflector and matrix material for the control drum. A spectral shift absorber $Gd_{2}O_{3}$ was used to prevent a sub-critical LSSNR from returning to criticality in a launch accident. The k_{eff} with the control drum in its innermost position is 0.954949, and k_{eff} reaches 1.00592 after 30 EFPY operation. The total mass of the active core is 160.65 kg. Additionally, 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, leading to uniform temperature distribution in the coolant flow field and reducing local temperature peaks. Based on the LSSNR scheme, several neutronic characteristics were analyzed. Results demonstrate that LSSNR has strongly negative reactivity coefficients due to thermal expansion of the liquid fuel, and the fission gas-induced pressure meets safety requirements. After 100 years following the end of core life, the total radioactivity of the reactor core is reduced by 99% to 7.1305 Ci.

Section II presents methodology and design goals. Section III introduces the preliminary design of LSSNR, followed by focused optimizations resulting in a finalized core configuration. Section IV presents thermal-hydraulic feasibility verification of LSSNR. Section V discusses neutronic analysis. Finally, Section VI summarizes conclusions.

METHODOLOGY AND DESIGN GOALS

Due to the complex neutron spectrum and geometric configuration of LSSNR, conventional "two-step" deterministic calculations 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. Since the Monte Carlo method is well-suited for reactors with arbitrary neutron spectra, the open-source Monte Carlo neutron transport code OpenMC [15], developed by the Computational Reactor Physics Group at MIT, was employed for neutronics and burnup analyses of LSSNR. The nuclear data library and depletion chain used in OpenMC calculations are based on the ENDF/B-VII.1 library [16]. 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 can dynamically broaden resonance cross sections based on user-defined temperature. Additionally, a Python API can be used to simplify modeling of complex reactor core geometries.

For space exploration, space nuclear reactor design primarily focuses on minimization of reactor core, long lifetime, and high safety. Table 1 compares different historical space reactors in terms of fuel enrichment, fissile material loading, core power, core mass, and lifetime. Space reactors are generally configured with high enrichment and characterized by fast spectra, eliminating neutron moderators to reduce weight and complexity. Reactor core mass is closely related to lifetime, thermal power, and fuel enrichment. For space reactors with lifetimes greater than 10 years and thermal power greater than 500 kW, reactor core mass and fuel enrichment are typically greater than 250 kg and 80%, respectively.

Due to launch restrictions and deep-space exploration mission requirements, space reactors have stringent design goals for weight, power, and lifetime. High power and long lifetime represent future development trends for space nuclear reactors. Design lifetime has increased from a few years to 12-15 years or even longer, while reactor core mass has been reduced to less than 500 kg. Additionally, high power density requires stronger heat transfer to reduce fuel temperature, necessitating new fuel element designs to enhance heat transfer. Furthermore, the fast neutron spectrum of space reactors weakens the Doppler effect, affecting operational safety. The liquid-solid dual-fuel space nuclear reactor proposed in this study can address this issue. Due to thermal expansion and contraction effects of liquid fuel, LSSNR exhibits more negative temperature and void reactivity coefficients, thereby enhancing inherent safety. Considering the advantages of combining solid fuel and molten salt, this study proposes higher design goals for LSSNR: (1) lifetime of 30 effective full power years (EFPY) with 1 MW thermal power; (2) reactor active core mass less than 200 kg; (3) more negative reactivity compared to conventional cooling systems; (4) no return to criticality under accident conditions; (5) improved heat transfer performance.

CONCEPT DESIGN OF LSSNR AND NEUTRONICS RESULTS

A. Fuel Element Design

The fuel element is one of the basic components of LSSNR and affects the neutronics characteristics of the 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 Fig. 1 Figure 1: see original paper, which is also applied for thermal-hydraulic feasibility analysis in Section IV. However, a torsionless cross-shaped spiral fuel element as shown in Fig. 1(b) was used in neutronics calculations since accurate modeling of complex geometry by OpenMC poses significant challenges. Previous neutronic studies on cross-shaped spiral fuel rods have demonstrated that the impact of torsionless cross-shaped spiral fuel rods on neutronics characteristics is negligible [20]. Additionally, the curved surfaces of the cross-shaped spiral fuel are approximated by right-angled surfaces.

To achieve a compact configuration, the reactor core of LSSNR adopts a hexagonal arrangement. The design of the hexagonal fuel lattice cell is shown in Fig. 2 [Figure 2: see original paper]. The fuel lattice cell consists of fuel, cladding, and coolant. In the preliminary design, based on design parameters of traditional space reactors [2, 7, 8, 21], the pitch of the hexagonal fuel elements is 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 remains between the fuel and cladding for thermal expansion. The material volume expansion coefficient and the linear expansion coefficient have the approximate relationship = 3 , and is defined by Eq. (1) [6]. Where T is temperature in K, V is material volume in cm^{3}, r indicates radius, ΔT means temperature change, and h is axial height. In this study, based on thermal-hydraulic results of LSSNR, the maximum temperature variation from cold to hot condition in the reactor core was determined to be approximately 800 K, which was used to define the He gap dimensions. The linear expansion coefficients of materials commonly used in space nuclear reactors such as UN, UO_{2}, and UC are respectively 9.9×10^{-6} (290 K to 1870 K), 12.83×10^{-6} (298 K to 2273 K), and 12.8×10^{-6} (298 K to 2000 K) [18], and the radial dimension changes are 0.00652 cm, 0.00845 cm, and 0.00843 cm, respectively. Thus, inner and outer He gaps of 0.005 cm can meet design requirements.

$$\Delta r = \frac{\sqrt{\pi(r+\Delta r)^{2h}} - \sqrt{\pi r^{2h}}}{\sqrt{\pi r^{2h}} \cdot \Delta T} \beta r^2 \cdot \Delta T + r^2 - r$$

LSSNR adopts liquid-solid fuel, with solid fuel playing the dominant role in neutronics characteristics. The effect of different types of solid fuel with varying U-235 enrichment on fuel element k_{inf} was calculated by OpenMC code, as shown in Fig. 3 [Figure 3: see original paper]. UN, UO_{2}, and UC [22, 23] commonly used in space reactors were employed, and the cladding material and molten salt were temporarily chosen as Mo-30Re and $^{7}LiF–BeF_{2}–UF_{4}$, respectively. In OpenMC calculation, 300 cycles with 500,000 neutron particles per cycle were adopted, with the first 100 cycles ignored in result tally, and the boundary condition is reflective. The results show that k_{inf} is directly proportional to U-235 enrichment for all fuel types. For the same U-235 enrichment, due to the moderation ability of C, the UC fuel element has a slightly larger k_{inf} than other cases, about 2% higher.

Carbide fuels have advantages over more widely studied oxide fuels in terms of higher thermal conductivity, which reduces peak centerline fuel temperatures and allows for fuel elements with higher linear power and larger size. The thermal conductivity of UC (18.8 W m^{-1} K^{-1}) is higher than that of UO_{2} (2.1 W m^{-1} K^{-1}) and UN (15.8 W m^{-1} K^{-1}). Its density (13.6 g cm^{-3}) is slightly lower than that of UN (14.31 g cm^{-3}). Even though UC has higher swelling and fission gas release, it remains selected as a candidate fuel material in this conceptual design research [24]. The swelling and fission gas release of UC fuel will be discussed in Section V. Therefore, UC with 44% enriched U-235 is initially selected as the solid fuel for parametric analysis at the assembly level. The U-235 enrichment will be further adjusted based on design requirements in subsequent studies.

The choice of fuel element cladding is another important consideration. For neutron economy, cladding material should have low density and small neutron absorption cross-section. For safety, it should have good compatibility with molten salt, high melting point, and excellent thermal conductivity. The effect of several cladding materials commonly used in space reactors on fuel element k_{inf} was studied, as listed in Table 2 [25]. In OpenMC calculation, a two-dimensional fuel element model with reflective boundary condition and UC solid fuel with 44% U-235 enrichment were employed. The comparison shows that Ta alloys have high melting points but are less favorable in terms of neutron economy and density. Ti alloys offer low density and good neutronic performance, but their thermal conductivity is lower than that of Zr and Ni alloys. Compared with Nb, Ta, and Ni alloys, Zr alloy provides lower density, better neutronic performance, and higher thermal conductivity.

Since molten salt flows through 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 [26], and such alloys are commonly used in molten salt reactors. Therefore, Zr alloy and Ni-based alloy are adopted as cladding materials for the inner and outer layers of the fuel element, respectively.

Three categories of fuel salt are generally used: (a) alkali fluorides (e.g., ^{7}LiF–KF, ^{7}LiF–NaK–KF), (b) fluoride salts containing ZrF_4 (e.g., ^{7}LiF–ZrF_4, NaF–ZrF_4), and (c) fluoride salts containing BeF_2 (e.g., ^{7}LiF–BeF_2, NaF–BeF_2). According to previous studies [27], the viscosity of alkali fluorides is less than that of molten salts containing ZrF_4 and BeF_2, and viscosity increases with increasing molar ratio of BeF_2 to ZrF_4. LSSNR chooses ^{7}LiF–KF–UF_4 (49.55-49.55-0.9 mol%) with 30% U-235 enrichment as liquid fuel.

B. Preliminary Design of LSSNR

The height-to-diameter (H/D) ratio of the reactor active core is usually greater than 1, which can increase the reactivity worth of control drums, shorten the heat transfer path, and increase the heat transfer area [28]. To achieve design goals of compactness and core mass 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 elements to collect fission gas released during operation. At both ends of the solid fuel, there are two 0.1 cm-thick Re layers, which serve as spectral absorbing material. Reflectors with heights of 6 cm and 7 cm are set at the bottom and top of the active core, respectively, as shown in Fig. 4 [Figure 4: see original paper]. To avoid robustness reduction caused by complex mechanical structure, control drums were used to control core reactivity, maintain a sub-critical state before entering orbit, and shut down the reactor after mission completion. As shown in Fig. 4, LSSNR is configured with 6 control drums, each having B_4C (B-10, 78.439 wt.%) coating with an opening angle of 120 degrees. Thus, 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 based on OpenMC calculation. In this study, reactor core k_{eff} values with different reflectors were calculated based on the core model shown in Fig. 4. Calculations with 300 cycles, 100 skipped cycles, and 1,000,000 neutron particles per cycle were performed in OpenMC. The physical parameters of reflector materials and reactor core k_{eff} are listed in Table 4 . By comparison, the core with BeO reflector shows better k_{eff} and has a higher melting point, while Zr_3Si_2 has 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 for the control drum.

LSSNR may re-enter the atmosphere and fall back to Earth in a launch accident. A sub-critical LSSNR surrounded by seawater or wet sand has the possibility of returning to criticality since the isotopes 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 smaller absorption cross-section in the fast spectrum region and larger cross-section in the thermal spectrum region, as shown in Fig. 5 [Figure 5: see original paper]. In LSSNR, a 0.02 cm-thick SSA layer was added outside the cladding. SSAs including $B_{4}C$, $^{149}Sm_{2}O_{3}$, $Eu_{2}O_{3}$, $Gd_{2}O_{3}$, and Rhenium are commonly employed in space reactors, with physical parameters listed in Table 4 , where $B_{4}C$, $Eu_{2}O_{3}$, and $Gd_{2}O_{3}$ are enriched with natural elements. In this study, reactivity penalties caused by different SSA materials were studied for three cases based on the preliminary LSSNR design: (1) initial core configuration (Fig. 4), (2) bare reactor core (no outer reflector) with vacuum boundary condition, and (3) bare reactor core surrounded by wet sand. In calculations, seawater consists of 96.9 wt.% $H_{2}O$ and 3.1 wt.% NaCl, and wet sand with density 2.16 g cm^{-3} consists of 85.8 wt.% SiO_{2} and 14.2 wt.% seawater.

The results are listed in Table 6 . It can be seen that $Gd_{2}O_{3}$ 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 remains supercritical. Thus, adopting SSA material in LSSNR is necessary. However, Rhenium has the weakest spectral shift absorption capability, and $^{10}B_{4}C$ caused the greatest reactivity penalty. $B_{4}C$ commonly used as 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 element has relatively better neutron economy and much smaller reactivity penalty, which is beneficial for the long lifetime design goal. Overall, $Gd_{2}O_{3}$ was adopted in LSSNR.

C. Control Drum Absorber Thicknesses

To maintain sufficient shutdown margin and meet the design goal of 30 EFPY lifetime, optimized thicknesses of the $B_{4}C$ coating in control drums were investigated. Variations of k_{eff} for absorber thickness ranging from 0.75 cm to 2.0 cm were calculated. To meet 30 EFPY operation, U-235 enrichment was adjusted simultaneously. The results are listed in Table 6 . It shows that as $B_{4}C$ 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 $B_{4}C$ thickness of 0.75 cm were adopted in LSSNR, and the variation of k_{eff} with operation time is shown in Fig. 6 [Figure 6: see original paper].

After launch, with all control drum absorbers closest to the active core, the control drum will be adjusted to make the reactor core critical. However, in some cases, the reactor core needs to be shut down by adjusting absorber location. Reactivity margins when one or more control drums are stuck need to be analyzed. For a control drum with 0.75 cm $B_{4}C$ thickness, each control drum reactivity worth is 2192 pcm. During startup from subcriticality, the reactor core cannot reach criticality if 5 or more control drums are stuck (k_{eff} changes from 0.954949 to 0.976864 for 5 stuck control drums). Conversely, the reactor core cannot shut down if 3 or more control drums are stuck (k_{eff} changes from 1.08644 to 1.02068 for 3 stuck control drums).

The k_{eff} of LSSNR with the control drum in its innermost position is 0.954949. After 30 EFPY operation, k_{eff} reaches 1.00592, which meets the operation lifetime requirement. The physical and design parameters of the optimized LSSNR are listed in Table 7 and Table 8 . The total mass of the active core is almost the same as the initial design scheme.

THERMAL-HYDRAULIC FEASIBILITY ANALYSIS OF THE LSSNR

In this section, the thermal-hydraulic feasibility of LSSNR is evaluated using the multi-physics software COMSOL. To reduce computational time for whole-core Computational Fluid Dynamics (CFD) calculations, a simplified model based on a 4/61 reactor core configuration as illustrated in Fig. 7 [Figure 7: see original paper] was employed. The position marked as "PA" in Fig. 7 was selected for subsequent data collection to ensure acquisition of relevant experimental parameters and facilitate comprehensive analysis.

Unlike neutronic calculations, no geometric simplifications were employed in thermal-hydraulic calculations. The rotation angle difference between the top surface and bottom surface of the cross-shaped spiral fuel rod is 360°, meaning it rotates 30° for every 3.6 cm in height.

The fluid-solid coupled interface in COMSOL was employed to solve heat transfer between liquid and solid fuel. An inlet flow velocity of 1 m s^{-1} and inlet temperature of 873 K [26] were employed for liquid fuel, with pressure used as the outlet boundary condition. Periodic boundary conditions and adiabatic boundary conditions were respectively adopted for the fluid region and solid region in the radial direction. The thermal power of the simulation model was set to 65 kW based on 1 MW for the whole core. In LSSNR, both liquid fuel and solid fuel can generate fission heat. According to neutronic calculations, a power ratio of 2000:1 for solid to liquid and uniform power density were employed in thermal-hydraulic calculations. The k− turbulence model was adopted with the turbulence model type being RANS. 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 mesh-induced error at this resolution is sufficiently small. The thermal-hydraulic parameters of liquid fuel and solid fuel used in calculations are listed in Table 9 , with nearly all parameters considered as functions of temperature. The unit of T in the table is K.

A. Flow Characteristics

Transverse flow is a key parameter characterizing radial fluid disturbances. It can lead to 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 Eq. (2), where u_{tra} is transverse velocity in m s^{-1}, u_x is X-direction velocity in m s^{-1}, and u_y is Y-direction velocity in m s^{-1}. The transverse velocity varies periodically with the structure at the same fluid location.

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

Fig. 8 [Figure 8: see original paper] shows the transverse flow distribution at heights of 10.8 cm, 14.7 cm, 16.2 cm, and 18.9 cm, corresponding to 0°, 22.5°, 45°, and 67.5° covering the first 90° rotation angle. The axial region of the second 90° rotation angle has similar characteristics. The solid fuel rods loaded in LSSNR are cross-shaped spiral in shape, which leads to significant transverse flow observed in the coolant channel, primarily concentrated around the elbows of the two blades of the cross-shaped spiral fuel rod. Transverse flow at the top position of the four blades of the cross-shaped fuel is minimal. Additionally, the transverse velocity of the coolant flow field at the channel center 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.

The twisted structure of the cross-shaped spiral fuel element enhances transverse flow. Turbulent kinetic energy based on Eq. (3) was also used to quantitatively study the movement characteristics of liquid fuel, where k is turbulent kinetic energy in m^{2} s^{-2}, U is mean velocity in m s^{-1}, and I is turbulence intensity, a dimensionless parameter usually defined as a statistical property of turbulent velocity fluctuations, specifically the ratio of standard deviation of turbulent velocity to mean flow velocity. Turbulence intensity can be used to measure the chaotic nature of fluid flow.

$$k = (U \cdot I)^2$$

Fig. 9 [Figure 9: see original paper] shows turbulent kinetic energy along the axial direction at PA for LSSNR. It presents a 90° cycle characteristic for LSSNR (90° rotation for every 10.8 cm). The complex structure of the cross-shaped spiral fuel results in drag of the fluid.

The pressure drop across LSSNR from inlet to outlet is 9387.4 Pa. Fig. 10 [Figure 10: see original paper] 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°. Peak pressure appears in the inner elbow region on the windward side of the spiral cross fuel, while pressure on the leeward side is relatively small. The complex structure of the cross-shaped spiral fuel increases flow resistance and lateral disturbance, resulting in uneven radial distribution of thermal-hydraulic parameters.

B. Heat Characteristics Analysis

The fuel element center temperature variation along axial height is shown in Fig. 11 [Figure 11: see original paper]. The temperature rise of the cross-shaped spiral fuel rod begins to slow down after 0.05 m. The maximum temperature of the spiral cross-shaped fuel rod is 1075.1 K, with a minimum temperature of 872.78 K, resulting in a temperature difference of 202.32 K. The structure of the cross-shaped spiral fuel element can effectively control fuel temperature and temperature difference between inlet and outlet.

Fig. 11 also shows the axial distribution of coolant temperature at the PA position. The coolant temperature of LSSNR begins to rise significantly at the 0.1 m position after a gradual increase in the inlet zone. It exhibits cyclic variation, with the maximum temperature difference reaching approximately 12 K. This phenomenon arises because the coolant flow area in the cross-shaped spiral fuel periodically varies due to the torsional geometry of the fuel rod. Consequently, coolant temperature exhibits alternating increases and decreases along axial height, while the overall trend shows an increase in the flow direction.

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

NEUTRONICS ANALYSIS OF LSSNR

Based on the above LSSNR design, several neutronic characteristics were analyzed including reactivity coefficients, criticality safety in launch accidents, fission gas behavior, and core radioactivity.

A. Reactivity Coefficients

Reactivity coefficients play an important role in core safety. LSSNR contains both solid fuel and molten salt fuel simultaneously; thus, two types of fuel temperature reactivity coefficients were calculated. It should be noted that solid fuel volume hardly changes with temperature variation. However, molten salt fuel density changes must be considered in calculating the fuel temperature reactivity coefficient. The relationship between molten salt fuel density and temperature is shown in Eq. (4) [30], where   means molten salt fuel density (g cm^{-3}) and T indicates molten salt fuel temperature (°C).

$$\rho = 2.49727 - 0.000619 \cdot T$$

Due to the hard neutron spectrum in LSSNR, the Doppler effect is relatively weak. OpenMC calculations adopted 2000 cycles, 800 skipped cycles, and 1,500,000 particles per cycle. The k_{eff} standard deviations are less than 1.9 pcm. Six temperature points at 100 K intervals 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 molten salt fuel temperature, and changing both temperatures. Additionally, coolant void reactivity worth was calculated. In LSSNR, molten salt fuel serves as both coolant and fuel, and two conditions including liquid fuel filling the core (0% void fraction) and complete emptying (100% void fraction) were calculated. The results are listed in Table 10 and Table 11 . The temperature reactivity coefficients of both solid and liquid fuels are negative, indicating inherent negative feedback. The void reactivity worth is -9426 pcm. The Doppler effect is weak for the fast neutron spectrum of LSSNR, and a large portion of the negative fuel temperature coefficient is provided by liquid fuel containing little U-235 due to its thermal expansion and contraction effects. Thus, LSSNR has more negative temperature coefficients compared to conventional solid-fuel space reactors (generally about -0.07 pcm/K).

B. Criticality Safety in a Launch Accident

LSSNR may re-enter the atmosphere and fall back to Earth in a launch accident [28]. A sub-critical LSSNR surrounded by seawater or wet sand has the possibility of returning to criticality since the isotopes of H in water or Si in sand will soften the neutron spectrum. Previous research has studied criticality safety of space reactors under 4 conditions [29]. It should be noted that the space reactor remains subcritical before entering orbit, i.e., all control drums rotate inward (absorbers closest to the active core). Thus, criticality safety at three extreme cases was analyzed: (1) bare core without reflector at vacuum boundary condition, (2) cold reactor core surrounded by water or wet sand, and (3) cold bare core surrounded by water or wet sand. The case of control drums rotating outward and reactor core surrounded by wet sand simultaneously is not considered. The results listed in Table 12 show that positive reactivity is introduced in any launch accident case, but LSSNR remains sub-critical. More positive reactivity is introduced for cores surrounded by wet sand than by seawater.

C. Fission Gas and Core Radioactivity Analysis

Fission gas, one type of fission product, will be generated in both solid fuel and molten salt fuel for LSSNR. Fission gas produced in solid fuel will be collected in the He gap and restricted by cladding from entering molten salt fuel, while fission gas generated in molten salt fuel will circulate throughout the primary loop. The pressure created by fission gas is important for cladding integrity and reactor safety. Furthermore, the effects of fission products and radionuclides from neutron activation should be analyzed in LSSNR design. Unlike water reactors, two types of fission gas, Xe and Kr, were considered in LSSNR. The fraction of fission products released from solid fuel to the 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 similar diffusion coefficients to UO_{2} fuel, and its UC R/B is about 40% when the burnup level is 69.9624 MW d kg^{-1} at the end of operation. This value was used for the most extreme calculation. In the calculation, 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 using the ideal gas equation of state. 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 in the inner fuel region is 5.538 MPa, which is relatively larger than that in the outer fuel region due to deeper burnup level. In LSSNR solid fuel elements, the inner cladding material is Zr-4 and the outer cladding material is Ni-base alloy. According to previous research [31, 32], these two cladding materials can withstand pressures in excess of 7 MPa.

The radioactivity of solid fuel and molten salt fuel after 30 EFPY was calculated, as shown in Table 14 and Fig. 12 [Figure 12: see original paper]. Actinides in LSSNR have small radioactivity. In the first 10 years after the end of core life, radioactivity decreases from 1.1639 $\times10^{3}$ Ci to 1.1405 $\times10^{3}$ 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 following the end of core life, the total radioactivity of the reactor core is reduced by 99% to 7.1305 Ci. After 300 years following the end of reactor core life, 90% of radioactivity comes from actinides, where Pu-238 (half-life 87.84 years), Pu-239 (half-life 2.411 $\times10^{4}$ years), and Pu-240 (half-life 6.561 $\times10^{3}$ years) constitute 64.57%.

CONCLUSIONS

Aiming to achieve higher design goals, a novel LSSNR reactor was preliminarily proposed in this study by combining molten salt fuel and solid fuel. LSSNR adopts a hexagonal layout with an active core pitch of 27.5 cm and contains 61 fuel assemblies. A He gap of 5 cm height is located at the bottom of the assembly to collect fission gas released during operation, and reflectors of 6 cm and 7 cm height are respectively located at the bottom and top of the active core. In LSSNR, $^{7}LiF–KF–UF_{4}$ (49.55-49.55-0.9 mol%) with 30% enrichment was employed for molten salt fuel, solid fuel adopts UC, and $Gd_{2}O_{3}$ serves as SSA to improve safety in launch accidents. Optimization of $B_{4}C$ absorber thickness in control drums shows that LSSNR with 80.98 wt.% solid fuel enrichment and B_4C thickness of 0.75 cm has sufficient shutdown margin and lower solid fuel enrichment to meet 30 EFPY operation lifetime. After optimization, the k_{eff} of LSSNR with the control drum in its innermost position is 0.954949. After 30 EFPY operation, k_{eff} reaches 1.00592, meeting the operation lifetime requirement. The total mass of the active core is 160.65 kg, which is less than 200 kg.

Additionally, an evaluation of the thermal-hydraulic feasibility of LSSNR was performed. The results indicate that the cross-shaped spiral fuel, due to its unique structure, induces more pronounced transverse churn within the channel, thereby enhancing heat transfer and improving heat removal from the fuel rods. The coolant flow characteristics are well-matched with the thermal output of the fuel, meeting the design thermal-hydraulic requirements.

Furthermore, reactivity coefficients, criticality safety in potential launch accidents, and the behavior of fission gases and core radioactivity were evaluated. Results demonstrate that LSSNR possesses strongly negative reactivity coefficients, and the fission gas-induced pressure meets safety requirements.

REFERENCES

[1] N. NASA, NASA technology roadmaps TA 3: Space power and energy storage, Tech. Rep. (NASA Technol, Roadmaps, 2020: 117-121, 158-165, 2015).

[2] M. S. El-Genk, Acta Astronautica 64, 833 (2009).

[3] S. F. Demuth, Progress in nuclear energy 42, 323 (2003).

[4] D. I. Poston, in AIP Conference Proceedings, Vol. 552 (American Institute of Physics, 2001) pp. 797–804.

[5] Z. Wu, L. Qi, L. Sun, M. Wu, H. Yang, and T. Liu, Annals of Nuclear Energy 194, 110054 (2023).

[6] A. Bushman, D. Carpenter, T. Ellis, S. Gallagher, M. Hershcovitch, M. Hine, E. Johnson, S. Kane, M. Presley, A. Roach, et al., "The martian surface reactor: An advanced nuclear power station for manned extraterrestrial exploration," (2004).

[7] M. S. El-Genk and J.-M. P. Tournier, Progress in Nuclear Energy 45, 25 (2004).

[8] J. C. King and M. S. El-Genk, Nuclear engineering and design 239, 2809 (2009).

[9] S. Li, D. Wang, Y. Jiang, W. Li, and W. Guo, Atomic Energy Science and Technology 52, 1186 (2018).

[10] M. Eades, J. Flanders, N. McMurray, R. Denning, X. Sun, W. Windl, and T. Blue, Journal of the British Interplanetary Society 64, 186 (2011).

[11] R. Kimura and T. Yoshida, Journal of Nuclear Science and Technology 50, 998 (2013).

[12] Q. Zhang, T. Cong, Y. Xiao, J. Li, C. Zeng, and H. Gu, Annals of Nuclear Energy 177, 109291 (2022).

[13] T. Conboy, T. McKrell, and M. Kazimi, Nuclear Technology 188, 139 (2014).

[14] Y. Fang, H. Qin, C. Wang, L. Zhou, J. Zhang, D. Zhang, W. Tian, G. Su, and S. Qiu, Annals of Nuclear Energy 161, 108434 (2021).

[15] P. K. Romano, N. E. Horelik, B. R. Herman, A. G. Nelson, B. Forget, and K. Smith, Annals of Nuclear Energy 82, 90 (2015).

[16] M. B. Chadwick, M. Herman, P. Obložinský, M. E. Dunn, Y. Danon, A. Kahler, D. L. Smith, B. Pritychenko, G. Arbanas, R. Arcilla, et al., Nuclear data sheets 112, 2887 (2011).

[17] M. S. El-Genk and J.-M. Tournier, in AIP Conference Proceedings, Vol. 699 (American Institute of Physics, 2004) pp. 658–

[18] J. Serp, M. Allibert, O. Beneš, S. Delpech, O. Feynberg, V. Ghetta, D. Heuer, D. Holcomb, V. Ignatiev, J. L. Kloosterman, et al., Progress in Nuclear Energy 77, 308 (2014).

[19] S. Yu, Q. Sun, H. Zhao, R. Yan, Y. Zou, and B. Lan, Nuclear Techniques 43 (2020).

[20] T. Zhang, W. Han, P. Shen, S. Huang, and K. Wang, Nucl. Power Eng. 44, 69 (2023).

[21] M. F. Khandaq, A. W. Harto, and A. Agung, Progress in Nuclear Energy 118, 103109 (2020).

[22] Y. Qian, W. Liu, and X. Sun, Atomic Energy Science and Technology 53, 45 (2019).

[23] B. Collin, Modeling and analysis of FCM UN TRISO fuel using the PARFUME code, Tech. Rep. (Idaho National Lab.(INL), Idaho Falls, ID (United States), 2013).

[24] Z. Xing, Design space exploration for salt cooled reactor systems, Ph.D. thesis (2022).

[25] M. S. El-Genk and J.-M. Tournier, Journal of Nuclear materials 340, 93 (2005).

[26] D. F. Williams, (2006).

[27] L. S. Mason, M. A. Gibson, and D. Poston, Nuclear and Emerging Technologies for Space (NETS-2013) (2013).

[28] L. de Holanda Mencarini and J. C. King, Nuclear Engineering and Design 340, 122 (2018).

[29] J. C. King and M. S. El-Genk, in AIP Conference Proceedings, Vol. 746 (American Institute of Physics, 2005) pp. 285–294.

[30] G. J. Janz, Journal of physical and chemical reference data 17 (1988).

[31] Y. Guérin, G. S. Was, and S. J. Zinkle, Mrs Bulletin 34, 10 (2009).

[32] S. J. Zinkle and G. Was, Acta Materialia 61, 735 (2013).

Note: Figure translations are in progress. See original paper for figures.