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A Comparative Analysis of Advanced Nuclear Fuel and structural Design in Advanced Fission Reactor

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ABSTRACT: The rapid transition toward low-carbon energy systems and increasing global energy demand have renewed interest in advanced nuclear fission technologies, particularly Generation IV reactors and Small Modular Reactors. This study aims to comparatively evaluate advanced nuclear fuels and structural materials based on their thermal, neutronic, mechanical, chemical, irradiation, and safety performance. An analytical review of scientific and technical literature from academic databases and authoritative nuclear organizations was conducted. The literature was qualitatively synthesized according to fuel type, structural material, reactor concept, coolant, and neutron spectrum. The findings indicate that uranium nitride, uranium silicide, and tri-structural isotropic fuels provide important advantages over conventional uranium dioxide fuel, including higher thermal conductivity, greater fuel density, improved high-temperature performance, and enhanced fission-product retention. Among structural materials, iron-chromium-aluminum alloys, silicon carbide composites, and high-entropy alloys demonstrate promising oxidation resistance, thermal stability, mechanical strength, and irradiation tolerance. However, their performance is strongly dependent on reactor type, neutron spectrum, coolant chemistry, operating temperature, and irradiation conditions. The review further shows that integrating advanced fuels and structural materials with passive safety systems and modular reactor architectures can improve safety, thermal efficiency, sustainability, and economic potential. Major challenges remain in irradiation qualification, corrosion, manufacturing, regulatory approval, economic feasibility, and spent-fuel management. Overall, coordinated development of advanced fuels and structural materials represents a promising pathway toward safer, more efficient, sustainable, and economically viable nuclear energy systems.

KEYWORDS: advanced nuclear fuel, accident tolerant fuel and passive safety system, generation IV reactor, structural material, small modular reactor.

INTRODUCTION

Nuclear energy has re-emerged as an important component of the global clean-energy transition and efforts to achieve carbon neutrality by 2050. Nuclear power currently contributes approximately 10% of global electricity generation and nearly one-third of carbon-free electricity (May & Werz, 2025; Tian, 2022). To meet increasing energy demand and support net-zero targets, the nuclear industry is advancing toward innovative fission technologies, including Small Modular Reactors (SMRs) and Generation IV reactor concepts such as Sodium-Cooled Fast Reactors (SFRs), High-Temperature Gas-Cooled Reactors (HTGRs), and Molten Salt Reactors (MSRs) (Hedayat, 2023; May & Werz, 2025). The successful deployment of these technologies depends not only on reactor design but also on the development of nuclear fuels and structural materials capable of maintaining their performance under severe thermal, mechanical, chemical, and irradiation conditions.

Conventional Light Water Reactors (LWRs) primarily use uranium dioxide (UO_2) fuel with zirconium-based cladding. Although this fuel–cladding system has demonstrated reliable performance over decades of commercial operation, its limitations under severe accident conditions have encouraged the development of advanced fuel systems. In particular, the Fukushima Daiichi accident demonstrated the importance of improving fuel and cladding behavior under loss-of-coolant and high-temperature conditions. At elevated temperatures, zirconium-based cladding can react with steam, generating hydrogen and potentially compromising cladding integrity (Chaudri et al., 2024; Rebak, 2023). Consequently, Accident-Tolerant Fuels (ATFs) and advanced cladding materials have become important research priorities (Li et al., 2024). Uranium nitride (UN) and uranium silicide (U_3Si_2) offer higher thermal conductivity and uranium density than UO_2, whereas Tri-structural Isotropic (TRISO) fuel incorporates multiple ceramic barriers that can provide effective fission-product retention at high temperatures (Li et al., 2024; Tian, 2022).

In parallel with fuel development, advanced structural materials are being investigated to address the demanding operating environments of advanced reactors. Iron-chromium-aluminum (FeCrAl) alloys, silicon carbide (SiC) composites, and High-Entropy Alloys (HEAs) have demonstrated promising resistance to oxidation, corrosion, irradiation damage, and high-temperature degradation (Čížek et al., 2021; Rebak, 2023). Their potential integration with advanced fuels, Small Modular Reactors, and passive safety systems may improve reactor resilience while reducing dependence on active safety components and mitigating some construction and operational challenges (Hedayat, 2023; NEA, 2024). Nevertheless, the performance of these materials is strongly dependent on reactor-specific conditions, including neutron spectrum, coolant chemistry, operating temperature, irradiation exposure, and fuel–cladding compatibility. Consequently, evaluating fuels or structural materials independently may not adequately represent their overall suitability for advanced reactor applications.

Despite substantial progress in individual fuel and material technologies, a significant research gap remains in the integrated and systematic comparison of advanced nuclear fuels and structural materials across different reactor concepts. Previous studies have extensively investigated fuels such as UN, U_3Si_2, and TRISO and structural materials such as FeCrAl, SiC, and HEAs; however, relatively limited attention has been given to comparing their combined thermal, neutronic, mechanical, chemical, irradiation, and safety performance within a common analytical framework. In particular, the interactions among fuel, cladding, structural materials, and coolant under reactor-specific operating conditions require further systematic assessment. Addressing this gap is important because the suitability of an advanced fuel cannot be determined independently of its surrounding structural and coolant environment.

Therefore, the aim of this study is to comparatively evaluate conventional UO_2–zirconium systems and advanced nuclear fuels and structural materials for application in SFRs, HTGRs, MSRs, and SMRs. The study specifically examines thermal and neutronic performance, mechanical and chemical stability, corrosion and oxidation resistance, irradiation tolerance, fuel–cladding compatibility, operating temperature, coolant characteristics, neutron spectrum, and passive safety performance. By integrating these factors into a common comparative framework, the study seeks to identify promising fuel–structural material combinations, clarify their major technical limitations, and evaluate the key barriers to their broader deployment and commercialization. The findings are intended to provide a systematic basis for improving the safety, efficiency, sustainability, and economic viability of advanced fission reactor systems.

MATERIALS AND METHODS

Study Design

This study employed a comparative analytical review design to systematically examine and compare advanced nuclear fuels and structural materials used or proposed for advanced fission reactor systems, with particular emphasis on Generation IV reactors and advanced small modular reactor (SMR) concepts. The methodology was based on a structured review and qualitative synthesis of published scientific and technical literature. The comparison focused on key nuclear, thermal, mechanical, chemical, and irradiation-related properties that influence fuel performance, structural integrity, reactor safety, and overall reactor efficiency.

Data Sources and Literature Search Strategy

Relevant scientific literature was identified through searches of major academic databases and scientific information sources, including ScienceDirect, Web of Science, Pub Med and Google Scholar. Additional technical information was obtained from authoritative organizations and institutional reports, including the International Atomic Energy Agency (IAEA), OECD Nuclear Energy Agency (OECD-NEA), and U.S. Department of Energy (DOE). The literature search used combinations of keywords and Boolean operators. The principal search terms included: advanced nuclear Fuel, Structural Material, Generation IV reactor, Small modular reactor, Accident tolerant Fuel and Passive safety system. The search was further refined by combining fuel-related terms with specific reactor technologies such as sodium-cooled, lead-cooled, gas-cooled, molten-salt, and supercritical-water-cooled reactors. The process of literature identification, screening, eligibility assessment, and final selection of the included studies is presented in the flow diagram shown in Figure 1 below.

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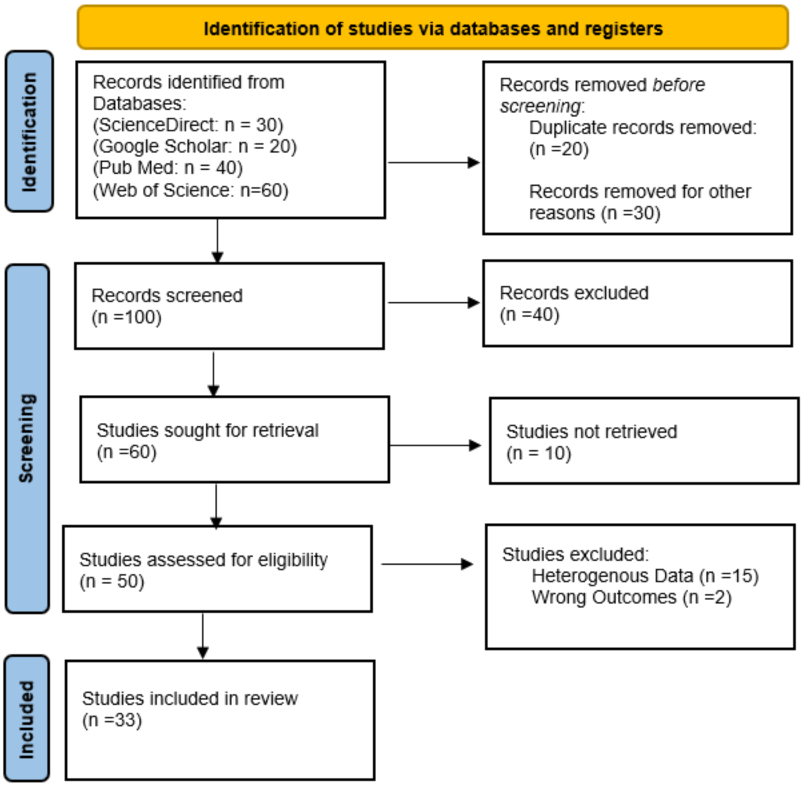

Figure 1. (PRISMA) flowchart of the literature search and study selection process.

Eligibility Criteria

Studies were considered eligible when they provided relevant information on the properties, performance, limitations, or applications of advanced nuclear fuels or structural materials for advanced fission reactor systems. Peer-reviewed research articles, review papers, conference proceedings, technical reports, and authoritative institutional publications were considered when they contained sufficient technical information for comparative analysis. Studies were excluded when they were unrelated to advanced fission reactor technologies, lacked relevant information on fuel or structural-material performance, were duplicate publications, or did not provide sufficient technical information for the intended comparison. Publications focusing exclusively on conventional reactor systems without relevance to advanced fuel or structural-material development were also excluded.

Data Collection and Extraction

Data were extracted from the selected literature using a structured comparative framework. For advanced nuclear fuels, the extracted parameters included fuel type, chemical composition, enrichment characteristics, thermal conductivity, melting point, fuel density, irradiation behavior, fission-product retention, swelling, fuel-cladding interaction, and accident tolerance. For structural materials, the extracted parameters included material composition, mechanical strength, thermal stability, corrosion resistance, radiation tolerance, creep resistance, swelling, embrittlement, compatibility with reactor coolants, and long-term structural integrity. Additional information concerning reactor type, operating temperature, coolant environment, neutron spectrum, fuel-cladding or fuel-structural-material compatibility, and safety characteristics was also collected to provide an appropriate basis for comparison.

Comparative Analytical Method

The extracted information was analyzed using a qualitative comparative approach. Advanced fuels and structural materials were evaluated according to their principal performance characteristics under the operating conditions of advanced fission reactors. The analysis emphasized the relationships among thermal performance, neutron irradiation behavior, mechanical stability, chemical compatibility, corrosion resistance, fuel integrity, and accident tolerance. The performance of different fuel types, including oxide, metallic, carbide, nitride, and TRISO-based fuels, was compared with respect to their suitability for different advanced reactor concepts. Similarly, structural materials such as austenitic and ferritic/martensitic steels, nickel-based alloys, zirconium-based materials, and refractory materials were comparatively evaluated according to their thermal, mechanical, irradiation, and corrosion-related properties. Where quantitative values were reported consistently across the literature, they were compared using common physical units and standardized parameters. Because the study was based on published literature rather than newly generated experimental or simulation data, no original reactor experiment or Monte Carlo calculation was performed.

Data Synthesis and Interpretation

The findings were synthesized according to reactor technology and material category. The comparative assessment considered the advantages, limitations, and technological challenges associated with each fuel and structural-material option. Particular attention was given to the compatibility between fuel, cladding, structural materials, and reactor coolant because material performance is strongly dependent on the combined thermal, chemical, mechanical, and irradiation environment. The final synthesis was used to identify the most significant material-selection considerations for advanced fission reactors and to determine research gaps related to fuel performance, structural degradation, irradiation resistance, corrosion, thermal efficiency, and long-term safety.

Quality and Consistency of the Literature

The reliability of the evidence was assessed by giving greater weight to peer-reviewed studies, recent review articles, established scientific databases, and technical publications from internationally recognized nuclear research organizations. Findings reported by multiple independent studies were considered to have greater evidentiary support. Differences in reported material properties were examined in relation to reactor operating conditions, experimental methods, material composition, irradiation conditions, and measurement techniques.

RESULTS

Advanced Nuclear Fuels and Structural Designs

The reviewed literature identified Accident Tolerant Fuels (ATFs), uranium nitride (UN), and tri-structural isotropic (TRISO) fuel as important advanced fuel options. UN provides higher thermal conductivity and a higher melting temperature than conventional uranium dioxide (UO_2) fuel (Li et al., 2024; Tian, 2022). TRISO fuel particles consist of a fuel kernel surrounded by five principal components: a buffer layer, inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC), with the kernel forming the central fuel region (Zhu et al., 2023). The structure of a TRISO particle is presented in Figure 2.

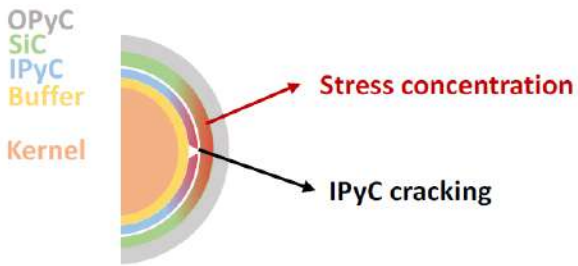

Figure 2. Axisymmetric representation of a TRISO particle without asphericity (Dhulipala et al., 2021)**.**

The reviewed studies also identified FeCrAl alloys, SiC composites, and high-entropy alloys (HEAs) as candidate structural materials for advanced reactors. FeCrAl alloys demonstrated high mechanical strength and reduced hydrogen generation during steam oxidation, while SiC composites showed high oxidation resistance and low neutron absorption characteristics (Čížek et al., 2021; Li et al., 2024).

Advanced Fuels and Designs in Fission Reactors

TRISO fuel is used or proposed for advanced reactor concepts, including the Xe-100 and Kairos Power Fluoride-Salt-Cooled High-Temperature Reactor (KP-FHR). Its multilayer ceramic structure provides barriers for fission-product retention at high temperatures

(Gadey et al., 2024). UN was also identified as a high-density ATF candidate because of its favorable thermal properties compared with UO_2 (Li et al., 2024). SiC composites are being evaluated for cladding and core applications because of their oxidation resistance and low neutron absorption (Chaudri et al., 2024). Advanced Small Modular Reactor (SMR) designs incorporate integral configurations in which major primary-system components are located within a single vessel. Several designs also employ passive cooling systems based on natural circulation (Wainwright et al., 2023). These characteristics are reported in the literature as important design features of advanced Generation IV systems (May & Werz, 2025).

Innovations in Next-Generation Nuclear Fission Technologies

The reviewed literature identified SMRs and Micro Modular Reactors (MMRs) as important approaches for flexible nuclear deployment. Artificial intelligence (AI) and digital-twin technologies have been investigated for reactor monitoring, predictive maintenance, and operational control (Lee, 2024). Heat-pipe-cooled reactors have also been investigated for remote terrestrial and space applications. These systems use passive heat-transfer mechanisms, including sodium- or potassium-filled heat pipes, together with Stirling power-conversion systems (Hedayat, 2023). Commercialization studies have further examined approaches for reducing scale-up and deployment requirements for advanced reactor systems (Buongiorno et al, 2018). The reviewed reactor concepts are classified by coolant type and neutron spectrum in Table 1.

Table 1. Characterization of advanced nuclear reactor systems by coolant and neutron spectrum (Buongiorno et al, 2018).

Coolant	Thermal Neutron Spectrum	Fast Neutron Spectrum
Helium	High-Temperature Gas-Cooled Reactor (HTGR) and Very-High-Temperature Reactor (VHTR)	Gas-Cooled Fast Reactor (GFR)
Molten Salt	Fluoride-Cooled High-Temperature Reactor (FHR), Molten Salt Reactor–Fluoride (MSR–fluoride)	Molten Salt Reactor–Chloride (MSR–chloride)

Advanced Fission Reactor Fuels and Structures

The reviewed studies identified thorium dioxide (ThO_2) as an alternative oxide fuel because of its chemical stability at elevated temperatures (Du Toit et al., 2024). Irradiation-induced defects were reported to reduce its thermal conductivity, with one study reporting a degradation of up to approximately 70% over the fuel lifetime (Du Toit et al., 2024). Doped fuel pellets and nanocrystalline structures have been investigated to address these changes and improve fission-gas retention and mechanical stability (Hurley et al., 2022). For structural applications, FeCrAl alloys and SiC composites have been investigated as alternatives to conventional zirconium-based cladding. FeCrAl alloys demonstrated favorable yield strength and creep resistance at temperatures approaching 800°C, while both FeCrAl and SiC showed reduced susceptibility to steam oxidation compared with conventional zirconium-based materials (Rebak, 2023).

Evaluating Advanced Nuclear Fuels and Structures

The reviewed literature employed experimental characterization, mechanistic modeling, and computational approaches to evaluate advanced fuel and structural materials. The Nuclear Energy Advanced Modeling and Simulation (NEAMS) initiative has focused on modeling fuel microstructure evolution and fuel performance under different reactor conditions (Gofryk, 2016). Fuel-cycle assessments have included the analysis of spent-fuel inventories, decay heat, and nuclide composition for evaluating advanced fuel-cycle performance and waste-management requirements (Rochman et al., 2024). Computational studies have also applied active-learning and multifidelity approaches to evaluate rare failure events in TRISO fuel particles (Dhulipala et al., 2021). These approaches provide information on fuel behavior, material degradation, and structural reliability under irradiation (Gofryk, 2016; Rochman et al., 2024). The buildup of the ^{106}Rh nuclide as a function of LWR fuel-assembly burnup is shown in Figure 3.

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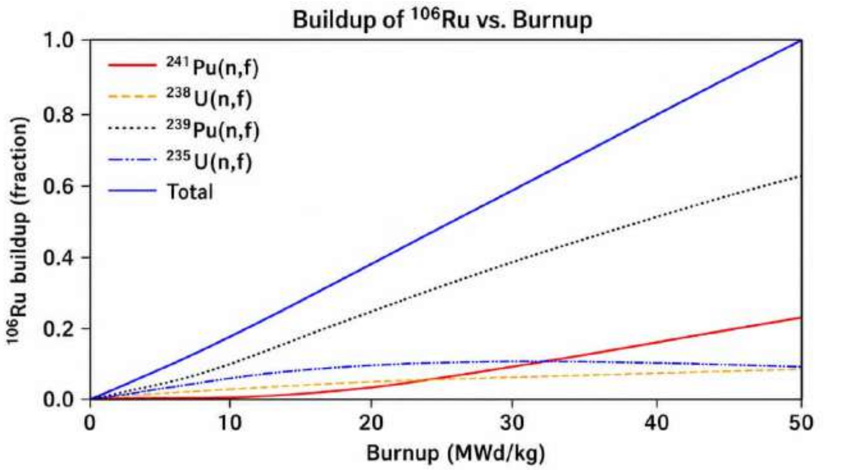

Figure 3. Buildup of the ^{106}Rh nuclide in an LWR as a function of assembly burnup for the four main fissioning nuclides (Rochman et al., 2024).

Advanced Nuclear Fuels and Structural Designs

The Kilo Power Reactor Using Stirling Technology (KRUSTY) combines high-temperature metallic fuel with Stirling power-conversion technology (Poston et al., 2020). The Small Advanced High Temperature Reactor (SmAHTR) concept uses TRISO fuel particles embedded in a graphite or SiC matrix and is designed for high-temperature operation with fission-product retention (Zhu et al., 2023). For molten-salt reactor systems, candidate fluoride-based coolants have been evaluated in relation to chemical stability, vapor pressure, and thermal properties (Williams, 2006). In fast reactors, irradiation-induced void swelling and irradiation creep have been identified as causes of dimensional changes in fuel cladding and structural components (Poplavsky & Zabudko, 1998). Ferritic-martensitic steels have therefore been investigated as candidate materials for these environments.

Comparative Review of Advanced Reactor Technologies

The reviewed Generation IV reactor concepts differ in coolant, neutron spectrum, fuel configuration, and operating temperature. High-Temperature Gas-Cooled Reactors (HTGRs) use helium coolant and graphite moderation, with reported outlet temperatures of approximately 700–850°C (Kadak, 2016). These systems use TRISO-coated fuel particles. Lead-Cooled Fast Reactors (LFRs) use liquid lead as the primary coolant. The high boiling point and chemical characteristics of lead are associated with passive-safety features (Grasso et al., 2014). Molten Salt Reactors (MSRs) can use liquid fuel containing dissolved fissile materials and have been investigated for online fuel management and minor-actinide transmutation (Schulenberg, 2022). Sodium-cooled fast reactors and supercritical-water-cooled reactors represent additional advanced reactor categories with different coolant and neutron-spectrum characteristics (Pioro, 2016).

Performance of Advanced Fuels and Material

U–10Zr metallic fuels have been investigated for sodium-cooled fast reactors because of their high energy density. Reported challenges include zirconium redistribution and fuel-cladding chemical interaction (FCCI). A machine-learning-based analysis reported approximately 67,000 fission-gas bubbles and an associated 35% reduction in thermal conductivity in the analyzed fuel conditions (Xu et al., 2022). Radiation-induced atomic displacements and transmutation products can alter the mechanical properties of structural materials. The principal degradation mechanisms reported include irradiation hardening, embrittlement, creep, growth, and void swelling (Rodriguez et al., 1984). The multilayer structure of a TRISO fuel particle is presented in Figure 4.

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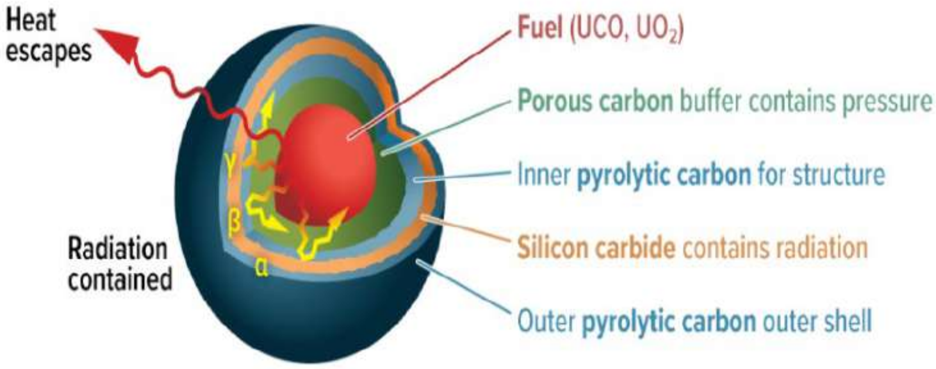

Figure 4. Layers of a tri-structural isotropic (TRISO) fuel particle (Gadey et al., 2024).

Innovations in Advanced Nuclear Fission Designs

The reviewed literature identified high-temperature materials, passive cooling, and modular configurations as major features of several advanced reactor concepts. The Advanced High-Temperature Reactor (AHTR) uses fluoride-salt coolant and operates at relatively low pressure (Holcomb et al., 2011). Fully ceramic microencapsulated (FCM) fuel incorporates TRISO particles within a SiC matrix, providing an additional barrier to fission-product release (Terrani et al., 2012). The Sodium-cooled Small Fast Long-life Reactor (4S) uses liquid sodium coolant and a compact core configuration for long-life operation. SMR concepts employ modular fabrication and standardized production approaches to reduce construction requirements and deployment time (Vujić et al., 2012).

DISCUSSION

The findings of this comparative analytical review indicate that the performance and suitability of advanced fission reactor systems depend on the integrated selection of nuclear fuels, structural materials, coolants, and safety systems. Consistent with previous studies, advanced fuels such as uranium nitride (UN), uranium silicide (U_3Si_2), and tri-structural isotropic (TRISO) fuel demonstrate important advantages over conventional uranium dioxide (UO_2) fuel in areas such as thermal performance, fuel density, high-temperature capability, and fission-product retention (Tian, 2022; Li et al., 2024; Rebak, 2023). These characteristics are particularly relevant to advanced reactor concepts operating at higher temperatures or under different neutron-spectrum conditions than conventional light water reactors.

The comparative findings further suggest that the advantages of individual fuels are application-dependent. Uranium nitride is particularly attractive because of its high thermal conductivity and uranium density, which can support improved heat removal and fuel utilization. In contrast, TRISO fuel provides multiple protective barriers and strong fission-product retention under high-temperature conditions, making it particularly suitable for high-temperature gas-cooled reactor applications. Uranium silicide also provides higher thermal conductivity and uranium density than UO_2, although its broader application requires further consideration of irradiation behavior, fabrication, and compatibility with cladding materials. These observations are generally consistent with the literature and demonstrate that fuel selection should consider the complete reactor operating environment rather than individual fuel properties alone.

Similar trends are observed for structural materials. The reviewed literature indicates that iron-chromium-aluminum (FeCrAl) alloys, silicon carbide (SiC) composites, and high-entropy alloys (HEAs) offer promising improvements in oxidation resistance, corrosion resistance, irradiation tolerance, and high-temperature stability compared with conventional zirconium-based materials (Čížek et al., 2021; Rebak, 2023). FeCrAl alloys are particularly promising for accident-tolerant applications because of their oxidation resistance, whereas SiC composites provide favorable high-temperature and corrosion-resistant characteristics. HEAs also show potential because of their combination of mechanical and irradiation-related properties, although their technological maturity and long-term qualification remain less established than those of conventional materials. Thus, the findings support previous research while emphasizing that material performance must be evaluated in relation to specific reactor conditions.

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The analysis also demonstrates that no single fuel or structural material is universally optimal across all advanced reactor concepts. Neutron spectrum, coolant chemistry, operating temperature, irradiation exposure, and fuel–cladding compatibility can substantially influence material performance. This finding supports the broader conclusion that advanced reactor materials should be selected through a system-level approach rather than by comparing isolated material properties. Integration with Small Modular Reactor (SMR) architectures and passive safety systems may further enhance the practical benefits of advanced materials by reducing dependence on active safety functions and supporting simplified reactor configurations (Hedayat, 2023; Vujić et al., 2012; Grasso et al., 2014)

A principal contribution of this study is the integrated comparison of advanced fuels and structural materials across different advanced reactor concepts. Rather than examining individual fuels or materials separately, the review considers thermal, neutronic, mechanical, chemical, irradiation, and safety characteristics within a common comparative framework. This multidisciplinary perspective provides a broader understanding of fuel–cladding–structure–coolant compatibility and can support material-selection decisions and the conceptual development of advanced reactor systems. In this respect, the study extends the existing literature by emphasizing the importance of compatibility among reactor components rather than focusing exclusively on the performance of individual materials.

Several limitations should nevertheless be considered when interpreting these findings. The study is based primarily on published literature and qualitative analytical comparison rather than new experimental measurements or original computational simulations. Differences among studies in material composition, experimental conditions, irradiation exposure, measurement methods, and operating temperatures limit the extent to which quantitative performance values can be directly compared. Furthermore, emerging materials such as HEAs and SiC composites require additional long-term irradiation qualification, manufacturing development, joining technologies, and regulatory assessment before their widespread deployment can be established.

The findings have practical implications for the design and development of advanced fission reactors, particularly where high-temperature performance, accident tolerance, irradiation resistance, and material compatibility are important design requirements. Future research should prioritize standardized experimental testing and quantitative comparison of advanced fuel–cladding systems, with particular attention to fuel swelling, embrittlement, creep, corrosion, thermal-conductivity degradation, and fuel–cladding chemical interactions. Coupled multiphysics studies integrating neutronic, thermal-hydraulic, and structural behavior could further improve understanding of material performance under realistic reactor conditions. In addition, manufacturing feasibility, joining methods, regulatory qualification, and techno-economic assessment should be incorporated into future evaluations.

Overall, the discussion indicates that the development of advanced nuclear energy systems should move from the evaluation of individual materials toward an integrated fuel–structure–coolant approach. Such a system-level perspective can help identify material combinations that are better matched to specific reactor concepts and operating environments, while providing a stronger basis for improving the safety, efficiency, sustainability, and practical deployment of Generation IV reactors and Small Modular Reactors.

CONCLUSION

This comparative analytical review demonstrates that the performance of advanced fission reactors depends strongly on the appropriate integration of nuclear fuels, structural materials, coolants, and safety systems. Compared with conventional uranium dioxide fuel and zirconium-based cladding, advanced fuels such as uranium nitride, uranium silicide, and tri-structural isotropic fuel offer important advantages in thermal performance, fuel density, high-temperature capability, and fission-product retention. Among the reviewed fuels, uranium nitride shows particular potential because of its high thermal conductivity and uranium density, while tri-structural isotropic fuel provides strong fission-product retention under high-temperature conditions. Similarly, iron-chromium-aluminum alloys and silicon carbide composites demonstrate promising oxidation, corrosion, irradiation, and high-temperature resistance compared with conventional cladding materials.

The analysis also indicates that no single fuel or structural material is universally optimal for all advanced reactor concepts. Material suitability depends on reactor-specific parameters, including neutron spectrum, coolant chemistry, operating temperature, irradiation conditions, and fuel–cladding compatibility. Therefore, an integrated fuel–cladding–structural material–coolant approach is essential for evaluating the overall performance and safety of advanced reactors. The findings further show that combining suitable advanced materials with Small Modular Reactor architectures and passive safety features has potential to support improved safety, efficiency, and practical deployment.

Despite these advantages, important challenges remain in material qualification, long-term irradiation performance, manufacturing, regulatory requirements, economic feasibility, and spent-fuel management. Future research should therefore focus on experimental validation, standardized material testing, integrated fuel–cladding assessment, and advanced modeling of long-term reactor behavior. Overall, the systematic comparison presented in this study provides a basis for selecting and developing advanced fuel and structural material combinations for safer, more efficient, sustainable, and economically viable Generation IV reactors and Small Modular Reactors.

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