ANALYZING FULLY CERAMIC MICROENCAPSULATED AS ACCIDENT TOLERANT FUEL

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ABSTRACT: A new kind of tri-structural isotropic (TRISO) particle fuel based on a silicon carbide matrix is the fully ceramic microencapsulated fuel (FCM). The FCM concept is an innovative, more tolerant fuel aggregating high robustness and safety. The FCM shows a high structural heterogeneity because four layers surround the kernel. In TRISO fuel, successive layers cover the kernel, such as porous carbon buffer, pyrolytic carbon, and silicon carbide layers. The buffer layer shows excellent retention of fission products, permitting long burn cycles and improving fuel efficiency. Options for kernel materials include uranium mononitride or uranium oxycarbide and composites with fertile materials. In pressurized water reactors (PWRs), the fuel assembly requires around 20% of uranium enrichment for 17x17 arrangements. Besides, the fuel's outer diameter and pitch must suffer changes. However, there are several thermal physical models from early that will be heritage for next-generation reactor designs.

1 I INTRODUCTION

Nuclear power plants are not just a short-term solution; they have a long lifespan, which should instill confidence in the sustainability of nuclear energy. The long operational lives of nuclear reactors in Latin America and the United States demonstrate the enduring nature of nuclear power and reassure us about its long-term advantages. In Latin America, seven nuclear reactors are operational. Brazil has two nuclear reactors producing 1.9 GW; Argentina produces 5% of the demand with three nuclear units; and Mexico, which produces 1.62 GW, or 4.5% of the demand, operates two nuclear units. In the United States, 93 nuclear thermal reactors operate across 55 plants spread over 28 states, representing around 94.7 GW, or 18% of electrical demand. Recent analyses show that nuclear energy accounts for about 10% of the world's electricity demand. The

Nine Mile Point Unit is the oldest operating reactor in America, inaugurated in December 1969. In America, nuclear reactors have an average age of about 42 years; half of the licensed units will operate until 2030 and 2040 [1]. For the past five decades, civilian power units using light water reactors (LWRs) have utilized uranium dioxide UO_2, a solid fuel with a low thermal efficiency of less than 35%.

Follow the Nautilus submarine (SSN-571), moved by a pressurized water reactor (PWR) in 1953, and start a rice involving no water-cooling designs. In 1957, it began with a sodium fast reactor (SFR) and planned to do Seawolf (SSN-575). In 1971, the Soviet Union commissioned the lead-bismuth-cooled fast reactors developed for the Alfa-class submarine, the so-called K-64, because of their reduced dimension, reached a speed of 40 knots and dived to a depth of 350 m using titanium hulls [2].

Prototypes may have an advantage in the public's acceptance of fast reactors, even though sodium-cooled reactors are a far more developed and standard technology. Around the world, advanced designs have used heavy liquid metal coolants (HLMC), like pure molten lead or lead-bismuth eutectic (LBE) alloys [3].

Lead-cooled designs' advantages include their very high boiling point, chemical inertness in contact with air or water, and ability to employ natural circulation. Thus, over time, the number of countries creating liquid metal reactors has increased, including Russia, China, the European Union, and the USA. However, Russia has dominated the world in lead-cooled reactors.

Thus, according to the Generation IV International Forum (GIF), which was realized in 2001, LFRs are a promising technology for producing electricity and hydrogen and managing actinides in a closed fuel cycle [4].

Its primary goal is to evaluate tri-structural-isotropic particle fuel, which is now the fuel for next-generation high-temperature gas-cooled and very-high-temperature reactors. Developers have studied six advanced designs based on early gas reactors, including helium-cooled and high-temperature gas-cooled reactors (HTGRs).

Operating as a consortium, the European Sustainable Nuclear Industrial Initiative (ESNII) has advanced in at least three designs [5]. The first is the Multi-Purpose Hybrid Research Reactor for High-Tech Applications (MYRRHA), which is an accelerator-driven system (ADS) with a 600 MeV linear accelerator (LINAC) cooled by lead-bismuth eutectic (LBE). The MYRRHA has a subcritical core coupled to a proton accelerator dedicated to radioisotope production for medical and industrial applications.

The ESNII has promoted the Advanced Lead-Cooled Fast Reactor European Demonstrator (ALFRED). ALFRED is a pool-type reactor with an electrical capacity of 125 MWe, operating with a forced primary circulation, a primary system pressure of less than 0.1 MPa, and a temperature range of 400-480 °C. It uses water or superheated steam as a secondary coolant.

The Pressurized Water Lead-Bismuth-Cooled Fast Reactor (PLFR) is a revolutionary nuclear reactor design that combines PWRs and lead fast reactor (LFR) elements. Russia has developed a few lead-cooled fast reactors, including the LFR-TL-X, BREST-OD-300, and SVBR-100, with an integral design based on a pool-type design [6], [7]. It operates with lead-bismuth eutectic (LBE) as its primary coolant, reducing the need for primary pumps and steam generators. Instead, feedwater is directly injected into the hot lead-bismuth eutectic at the reactor core outlet.

Westinghouse is developing the LFR, a fast neutron spectrum reactor with a ~465 MW capacity. This passively safe modular reactor uses lead as a coolant. Its boiling point exceeding 1700 °C allows high-temperature operation at atmospheric pressure, increasing efficiency and reducing capital costs.

Following nuclear trends, the US developed the small lead-cooled fast reactor (SSTAR) in 2008, which has a 30-year lifespan. The China Lead-Based Research Reactor (CLEAR-I), a thermal power 10 MW, operated in 2014 and uses Generation IV lead-cooled fast reactor technology [8]. HLMC is actively developing experimental facilities worldwide, but there is a need to improve knowledge of heavy-liquid metal (HLM) coolant technology.

The high-temperature reactor designs operate at temperatures between 750 °C and 950 °C. They have used two types of cores: prismatic block or pebble-bed, with TRISO fuel particles, helium coolant, and graphite as moderators. China operates the High-Temperature Gas-Cooled Reactor Pebble Bed Module (HTR-PM), a pebble bed core 3 m in diameter and 11 m in height, connected to the grid in 2021 [9]. The module boasts an innovative design, featuring a 250 MW pebble-bed modular reactor with a power density ranging from 3.2 MW/m^3 to 6.6 MW/m^3, and it connects two reactors to a single steam turbine.

Helium coolant went into the HTR-PM at a mass flow rate of 96 kg/s at 250 °C and a pressure of 7 MPa. An active core heated it, mixed it, and sent it to the steam generator at a temperature of 750 °C. The HTR-PM utilizes spherical fuel elements that contain 7 g of heavy metal and 8.5% U-235 enrichment. Fissile kernels are coated with pyrolytic carbon layers that permit slight neutron moderation. The HTR-PM employs a prismatic block with graphite as a moderator. Each reactor contains 400,000 TRISO pebbles with a 6 cm diameter, resulting in an average fuel power density of 85.7 kW/kgU. In general, TRISO particle fuel employs fissions per initial metal atom (FIMA), and for PWRs, it has used the unit mass of the initial heavy metal (GWd/tHM). FIMA indicates physical consumption of nuclides, while burnup is practical for power applications, and 10% FIMA is around 100 GWd/tHM.

GIF’s research has sparked interest in non-water-cooled reactors, such as sodium-cooled, lead-cooled, high-temperature, gas-cooled, and molten salt-cooled reactors. The AVR (Arbeitsgemeinschaft Versuchsreaktor) reactor designs have influenced the development of very high-temperature reactors (VHTRs) within the GIF framework. The AVR was a prototype high-temperature gas-cooled reactor (HTGR) operated in Germany from 1967 to 1988. When TRISO kernels are based only on UO_2, they can produce too much carbon monoxide, leading to high pressure, SIC layer corrosion, and U-bearing phase migration.

2 I FULLY CERAMIC MICROENCAPSULATED

FCM spreads out a progression of tri-structural isotropic fuel particles in a SiC matrix, ensuring safety at all times. FCM shows several positive features, such as good oxidation resistance, high thermal conductivity, high chemical stability, high fission product tolerance, substantial radiation resistance, and corrosion resistance—all contributing to its reliability and safety. The FCM idea that links the stability of TRISO particles and the SiC matrix to stay stable when exposed to radiation at 1800 °C is now a strong choice [10].

In the nuclear industry, standard TRISO fuel has radioactive fission products covered in layers of ceramics. A fully dense silicon carbide matrix surrounds it, offering a highly rugged and stable fuel with exceptional high-temperature stability. The design of FCM fuel prioritizes safety, incorporating numerous barriers to prevent the dispersion of fission products. [11].

The advanced design uses microencapsulated fuel, keeping all fission products inside each TRISO spheric fuel. FCM technology is safer than other fuel types that operate with multiple barriers to prevent the spread of fission products, ensuring mechanical stability and efficient heat transfer [12]. In FCM fuel production, high-density silicon carbide has prospered for TRISO fuel compacts [13]. This material is thermally conductive and radiation-tolerant, providing a very efficient barrier to fission product dispersion and enhancing TRISO's multiple barriers. Since 1982, we have been making oxicarbide kernels using a sol-gel process. This process produces UO_3+C gel spheres, which undergo heating to transform into UO_2+C, UO_2+UC, and UO_2+UC.

The FCM fuel design utilized the TRISO layers. Four groups comprise these layers: outer pyrolytic carbon (OPyC), inner pyrolytic carbon (IPyC), silicon carbide (SiC), and buffer pyrolytic carbon (PyC). Each layer has a primary role, and the SiC layer serves as both the pressure vessel and the primary barrier for fission product (FP) release [14].

ATF fuel, particularly the fully ceramic microencapsulated (FCM) fuel, shows promise over regular nuclear fuel in specific scenarios. In situations with a loss of coolant, ATF fuel is less likely to produce hydrogen, does not let radioactive fission products escape, and performs better at cooling. Table I displays the characteristics of HTGR TRISO fuel used in Germany [15].

Layers	**HGTR TRISO**				**FCM**	
Kernel Fuel	UN-TRISO (μm)	AGR-2 (μm)	BR-22 (μm)	91F-1A (μm)	Thickness (μm)	Density (g/cm^3)
Kernel	400±10	507.7±11.9	544±9.1	551±9.9	350–600	10.06
Buffer	75±8.5	97.7±9.9	97.4±9.1	97.3±12	100	1.05
IPyC	25±2.5	41.9±3.2	32.9±3.4	32.1±3.4	35	1.90
SiC	35±1.5	37.5±1.2	33.7±1.6	34.2±1.7	35	3.18
OPyC	25±2.5	45.6±2.4	39.3±3.1	38.6±1.7	40	1.90

Table I: Physical properties of kernel, buffer, PyC, and SiC used for TRISO-based FCM fuels.

The AGR-2 experiments work with TRISO-coated UO_2 fuel particles under irradiation conditions. Like AGR-2, the BR-22 experiment measures fuel response under different conditions and its ability to retain fission products. In the AGR-2 experiment, UCO and UO_2 fuels achieved a burnup of 13.2% and 10.7% FIMA, respectively. The peak temperature for UCO fuel reached around 1360 °C.

2.1 Fuel Codes

Between 1966 and 2004, researchers built several fuel performance codes for TRISO fuel. Researchers investigated different ways that things can break. The most basic is the in-pile effect, which occurs when gas pressure builds up in porous buffer layers and causes stresses around the SiC layer. They mainly studied stable Xe, Kr, and CO [16].

The earliest fuel performance codes created by physical TRISO models started with a detailed description of the gas reactor and the pebble bed. The parties involved in the evolution of TRISO fuel were the Idaho National Laboratory (INL), Lawrence Livermore National Laboratory, the Commission d'Energie Atomique (CEA), the Massachusetts Institute of Technology (MIT), British Nuclear Fuels (BNF), and the Japan Atomic Energy Research Institute.

The Germans FRESCO and PANAMA (Pastrile Failure After Nabielek and Martin) were the first to develop coated fuel performance codes covering one-dimensional or three-dimensional problems. PANAMA was all about one-dimensional stress analysis and was crucial for figuring out how things fail, like gas pressure buildup and stresses on the silicon carbide layer. The first German codes were essential for figuring out how coated particles break, like how gas pressure builds up and stresses the silicon carbide (SiC) layer. The Research Center Julich's introduction of the STACY came later, starting in the 1980s. Concurrent initiatives arose, such as the UK code STAPLE and STRESS3, the French code ATLAS, and PASTA from the Netherlands. The Idaho National Laboratory developed the Particle Fuel Model (PARFUME) based on an integrated mechanistic coated particle fuel model. The model computes the diffusion of fission products and aids in estimating the release of fission gas (FGR) through recoil and diffusion.

European codes include PANAMA, STRESS3, ATLAS, and STACY, while American codes include PARFUME, TIMCOAT, and BISON. High-temperature gas reactors and pebble bed prismatic systems like PARFUME, which INL developed, served as the foundation for developing TRISO codes. CEA used the ATLAS code to simulate the behavior of TRISO, a technology commonly used in HTRs and fast breeder reactors. The ATLAS code identifies the percentage of fuel particles that fail under typical and unforeseen circumstances. Besides, ATLAS contains fission gas release advanced models coupled with statistical analysis.

Moreover, the COPA code from South Korea and the GOLT code from Russia are widely used. Tools like BISON, developed and built on the Multiphysics Object-Oriented

Simulation Environment (MOOSE) by the Idaho National Laboratory, enable today's simulation of the FCM concept. Tools like BISON allow us to simulate today's FCM concept.

2.2 Technology of coated particle fuel

From 1959 to 1965, the United Kingdom constructed the innovative HTGR known as the Dragon reactor, which is located in Winfrith Heath in Dorset. It was the first experimental HTGR, and it operated from 1965 to 1976. Dragon Design uses spherical pellets to adopt helium coolant and graphite as neutron moderators. Over the years, two designs have dominated the high-temperature gas reactor (HTGR). Pebble beds (PBRs) and prismatic block reactors (PBRs) operate from 700 °C to 1000 °C. The standard HTGR can operate at a pressure of 100 atmospheres and a temperature of up to 900 °C, enabling better thermodynamic conditions and leading to a higher thermal efficiency of around 38%. Today, modular reactors that produce 100 MW to 200 MW are considered generation-IV designs; they operate with gas turbines and TRISO fuel, reaching 48% efficiency. A graphite layer surrounding TRISO fuel, which exhibits the same finality as a moderate neutron flux, is crucial to the HTGR design. In the last decade, the TRISO fuel has garnered significant interest in the industry with its four layers of pyrolytic carbon and ceramic materials surrounding a uranium dioxide (UO_2) kernel.

2.3 New Trends of FCM Technology

In 2022, BWX Technologies, in collaboration with the US Department of Defense, supported by the Department of Energy (DOE), Idaho National Laboratory (INL), and the National Aeronautics and Space Administration (NASA), started plans to TRISO manufacturing. Framatome, the primary French supplier of nuclear technology, collaborated with the American Ultra Safe Nuclear Corporation (USNC) to develop the Micro-Modular Reactor (MMR®) platform. Moreover, Framatome and USNC have divulged strategies to produce fourth-generation designs using TRISO fuel particles. The University of California, Berkeley (UCB) is developing the Mark 1 pebble-bed FHR (Mk1 PB-FHR), which uses TRISO fuel for cooling. The Mk1 uses $LiF\text{-}BeF_2$ (FLIBE), a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF_2), in a 2 to 1 ratio (66–34 mol%), as a coolant. It operates with TRISO pebbles that are 3 cm diameter and works with molten fluoride salt.

PBR disperses TRISO fuel particles into graphite pebbles, while popular gas-cooled reactor designs use prismatic blocks. The fuel in these designs consists of billions of multilayered TRISO particles, each ranging in diameter from 750 to 830 μm, and dispersed in various forms such as spheres, pebbles, or circular cylindrical forms.

Carbon layers in the FCM fuel design provide thermal insulation, chemical stability, and mechanical strength to fuel particles. The porous buffer layer lets fission products and gases in, slowing fission fragmentation and making it easier for particle sizes to change. Together with PyC layers, they create a barrier to fission products. Figure 1 depicts FCM fuel spheres in a silicon carbide matrix.

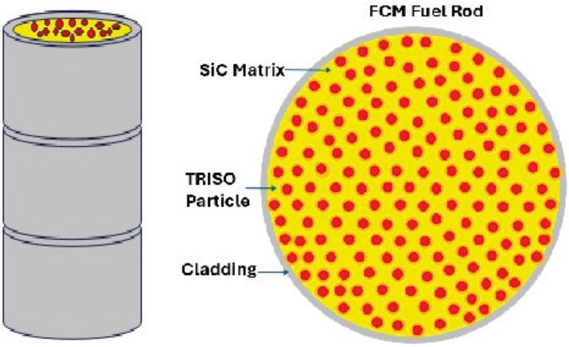

Figure 1. Fully ceramic microencapsulated is used for pressurized water reactors.

Silicon carbide became vital to the FCM fuel design to minimize solid fission products. The SiC layer is the principal barrier for fission products and must offer outstanding mechanical strength and temperature stability. It improves the fuel's safety and efficiency by averting the effects of chemical attack, radioactive material leakage, and crack deflection. The FCM comprises round particles with a fissile core, pyrolytic carbon layers on the inside and outside, a porous carbon buffer, and a silicon carbide layer that is 35 μm thick. The FCM fuel design comprises coated particles encased in a silicon carbide (SiC) matrix that can handle neutron radiation.

FCM fuel consists of TRISO fuel particles embedded in a SiC matrix, which shows high radiation tolerance and improved gas retention. Ceramic materials hold the particles in place, ensuring they comprise about 35–40% of the total volume. FCM replaces the graphite matrix with a SiC matrix, which shows high radiation tolerance and improves FP retention. Under regular operation, the SiC matrix acts as an additional barrier for FGR and improves oxidation resistance. In PWRS, the FCM reaches higher burnup levels. The SiC matrix improves resistance to fast neutron flux, reducing swelling and irradiation creep rates.

2.4 SiC Manufacture Route

Pressurized water reactors also use fuel rods with cylindrical pellets coated in zirconium or alloys like Kanthal APMT or based on SiC technology. In the last decade, fuel designers have intensified their efforts to fully ceramic microencapsulate fuel to improve fuel safety and efficiency by preventing chemical attacks, radioactive material release, and crack deflection.

In addition, SiC nuclear applications have been under investigation for over 50 years. Initially, researchers focused on replacing zircaloy with a monolithic SiC layer and fabricating the SIC layer for TRISO fuel in gas-cooled reactors.

Accident-Tolerance Fuel (ATF) tries to use SiC/SiC composites instead of zircaloy. Chemical vapor infiltration (CVI) or chemical vapor deposition (CVD) are the processes used to create these composites. CVD is the chemical reaction of gaseous precursors to make a solid material, while CVI is the deposition of SiC into a porous preform. However, CVD is famous for manufacturing SiC layers in TRISO fuel spheres. The electronic industry has tested various forms of chemical vapor deposition, such as laser chemical vapor deposition (LCVD) and plasma polimization. Sumarly, LCVD is a variation of (CVD) that uses lasers to heat the substrate locally, improve the deposition rate, and allow for precise control of the process. The semiconductor industry widely recognizes the laser methodology for its high purity. A crucial technique for fabricating high-quality ceramic matrix composites (CMCs), including silicon carbide (SiC) composites, is the Chemical Vapor Infiltration (CVI) process. Table II compares the physical properties of different routes to produce silicon carbide material.

Properties	**PyC**	**CVI-SiC**	**CVD-SiC**	**NITE-SiC**
Density (g/cm^3)	1.90	2.3	3.18	3.21
Thermal conductivity (W/m K)	4	100	120	13.9
Thermal expansion coefficient (10^{-6}/K)	5.7	3.5	4.9	4.5
Specific heat (J/kg K)	720	670	620	1200
Elastic modulus (GPa)	47	207	340	400
Poisson ratio	0.23	0.12	0.13	0.20

Table II. Comparison of physical properties of PyC, CVI-SiC, CVD-SiC, and NITE-SiC

The CVI route starts with the preparation phase, beginning with a porous performance. The next step is infiltration, introducing a precursor gas into a reactor containing the precursor. Then, the chemical reaction starts. The last phase is densification. Over time, the continuous deposition fills the pores, densifying the material and forming a solid matrix around the fibers.

They have produced high-quality silicon carbide (SiC) composites using the nanofiltration and transient eutectic (NITE) processes. The NITE method uses SiC nanopowders and certain sintering additives like aluminum oxide (Al_2O_3) and yttrium oxide (Y_2O_3). The NITE process then exposes the infiltrated preform to elevated temperatures (approximately 1750–1800 °C) and pressures (15–20 MPa) to attain densification. The transient eutectic phase occurs during sintering. The transient eutectic phase forms, which helps get the density close to the theoretical level and strengthens the bonds between the fibers and the matrix. Sintering of SiC is difficult because of its high melting point of over 2500 °C.

Silicon carbide sintering has at least three historical phases: reaction sintering (RS), hot pressing, polymer infiltration, and the liquid phase route. The first manufacturing route based on the reaction sintering (RS) method started around 1975 and greatly influenced SiC/SiC composite production. Reaction sintering comprises four phases: saturation with the green body, a compacted mixture of SiC powder, and a carbon source. It is prepared through slip casting, dry pressing, or cold isostatic pressing. In the second phase, a silicon infiltration process starts, heating it above 1500 °C in a vacuum or inert atmosphere. The molten silicon reacts with the carbon source, producing a green body, creating a β-SiC bonding and a dense ceramic structure.

SiC-SiC composites are ideal for the fabrication of continuous fibers. For this reason, suppliers looked at an old powder metallurgy method for adding liquid silicon that uses chemical vapor infiltration (CVI) and chemical vapor infiltration (CVD). In the 1980s, researchers permeated SiC fiber with a SiC precursor polymer by pyrolyzing the polymer in situ into SiC—a process known as polymer infiltration (PIP). The practical objective comprises deep penetration of Si and C in open pores. During fabrication, the pyrolyze process is executed at high temperatures of 800 °C to 1300 °C after infiltration.

The powder mixture employs hot-pressing sintering at 1750°C–1900°C. As a result, using a liquid phase to help the sintering process produces a high-dense SiC composite with better heat transfer. Introduced in Japan in 1990, the spark plasma sintering (SPS) route permits the sintering of SiC powder using pulsed electric current and pressure to SiC powder with low porosity. Using this technique, various nuclear laboratories have developed fully ceramic microencapsulated material with a high particle loading capacity.

At the same time, the FCM manufacturing route has employed a hot press method, adding mixed, small amounts of additives such as 1.75 wt% yttria (Y_2O_3), 3.25 wt% alumina (Al_2O_3), and 2.0 wt% silica (SiO_2). As a result, it shows excellent structural properties, including flexural strength at high temperatures (725 ± 68 MPa at 1200 °C, α-SiC) and a high melting point of 2730 °C.

Recently, research has arisen on advanced kinds of inert matrices to replace SiC, such as MgO, $MgAl_2O_4$, $Y_3Al_5O_{12}$, and CeO_{2-x}. The production of the SiC matrix is increasingly using nanofiltration. The transient eutectic-phase (NITE) method improves FCM fuel at low temperatures. The novel NITE process makes composites of a unidirectional silicon carbide fiber-reinforced SiC matrix (SiC/SiC).

FCM fuel has TRISO particles mixed in with a dense silicon carbide matrix. NITE gives the structure strength and keeps the particles in place. This combination makes the fuel highly resistant to high temperatures and radiation and capable of withstanding severe reactor conditions. Initially, we tested the vacuum deposition method in the CVD process, producing the CVD-SiC matrix. However, laboratories replaced it with the NITE-SIC method, which is more stable at temperatures of 1000 °C.

Kernel fission spreads the TRISO particles, which are much smaller than the FCM pellets, into the SiC matrix to act as heat sources. The packing fraction determines a more symmetric temperature distribution, and the power of each particle can create non-uniformity.

The FCM pellets are much bigger than the TRISO particles. The TRISO particles are heat sources spread into the SiC matrix by kernel fission. The packing fraction determines a more symmetric temperature distribution, and the power of each particle can create non-uniformity.

ATF programs commend the FCM fuel for its improved performance and dependability. Furthermore, FCM fuel demonstrates excellent stability in both standard and accident scenarios.

3 | ANALYZE THE PERFORMANCE OF MATERIALS

In general, physical properties such as thermal conductivity, specific heat, and coefficient of thermal expansion (CTE), are crucial to the performance of FCM fuel. Specific heat, thermal conductivity, and CTE are temperature functions that depend on neutron irradiation. Table III shows the thermal conductivity, thermal diffusivity, specific heat capacity, and density of TRISO layers.

TRISO layer	**Thermal diffusivity (10^{-6} m²/s)**	**Thermal conductivity (W/m K)**	**Specific heat capacity (J/kg K)**	**Density (Kg/m³)**
Buffer	4.07±0.60	5.65±0.84	730.5±0.65	1900
IPyC	6.09±1.38	8.46±1.92	731.1±1.5	1900
SiC	48.37±3.13	85.75±5.54	554.0±3.5	3200
OpYC	3.88±0.76	5.39±1.06	731.3±0.90	1900

Table III. Thermal properties of TRISO layers

TRISO particles, typically composed of uranium dioxide (UO_2), facilitate heat transfer. Early investigations demonstrated that they substantially impact thermal conductivity under particular conditions. Figure 2 shows the thermal conductivity of TRISO components.

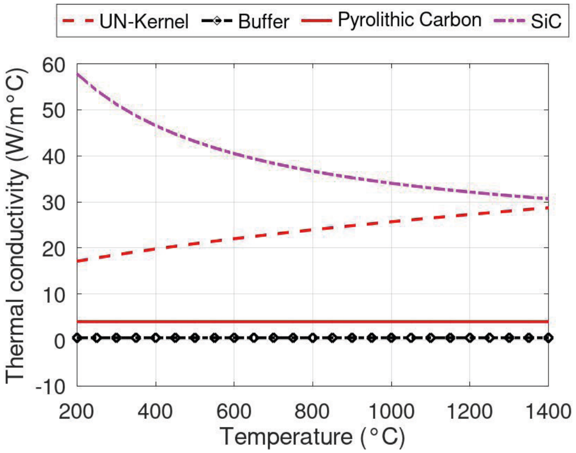

Figure 2. Thermal conductivity: uranium nitride (UN) buffer, pyrolytic carbon, and silicon carbide layer.

For instance, UO_2's thermal conductivity is relatively low compared to other potential nuclear fuels, such as uranium nitride (UN) or uranium silicide (U_3Si_2), which have higher thermal conductivity.

When conditions change quickly, we use nanosecond time-domain techniques like thermos reflectance to measure thermal conductivity in the SiC layer, IPyC, and OPyC. Today, thermos reflectance has become the principal approach to mapping the thermal properties of TRISO particles up to 1000 °C.

Pyrocarbon layers have shown significant porosity because the porosity buffer layer has a low heat capacity. Pyrolytic carbon layers (IPyC and OPyC) increase the heat capacities, similar to graphite. The high heat capacity of the SiC layer ensures the preservation of structural integrity even at elevated temperatures.

With their lower thermal expansion coefficient than UO_2, UCO kernels provide a reliable solution for structural integrity at high temperatures. However, the uranium nitride kernels perform better than the UO_2 kernels because they are better at conducting heat and have a lower thermal expansion coefficient. They also show higher resistance to thermal stress. Figure 3 depicts the heat capacity of layers of TRISO.

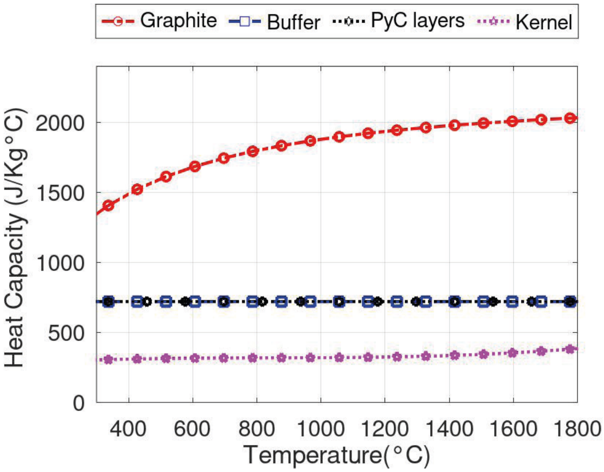

Figure 3. Specific heat capacity of TRSO material layers

The standard UO_2 kernels have a higher thermal expansion coefficient but good stability. Pyrolytic carbon layers expand in different directions and exhibit anisotropic thermal expansion responses. SiC exhibits a minimal thermal expansion coefficient at elevated temperatures. Figure 4 illustrates the coefficient of thermal expansion of TRISO particle fuel.

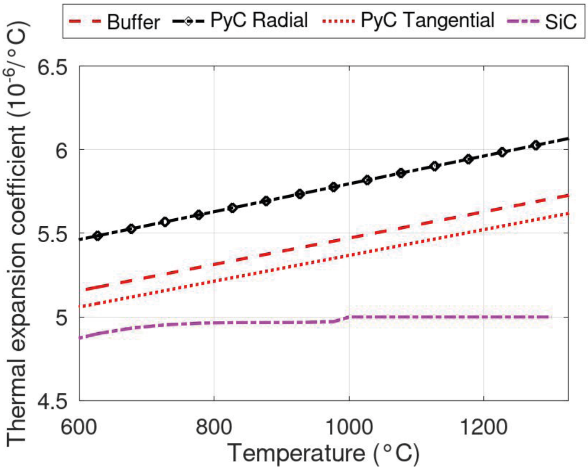

Figure 4. Coefficient of thermal expansion of buffer, anisotropic PyC, and SiC layers.

An essential parameter for measuring the release of fission products is their' release-to-birth ratio (R/B). Under regular operation, we conduct the failure analysis at temperatures below 1250 °C; under transient scenarios, the temperature can reach over 1600 °C. Also, there is a limit to contamination in the outer PyC layer ($<10^{-5}$) with a low level of defective particles ($\sim 10^{-5}$). However, fission products release krypton, strontium, silver, and cesium—fission products like palladium, silver, and strontium, speeding up the breakdown of pyrolytic layers. Moreover, palladium silicide or deposits in SiC layers lead to failures.

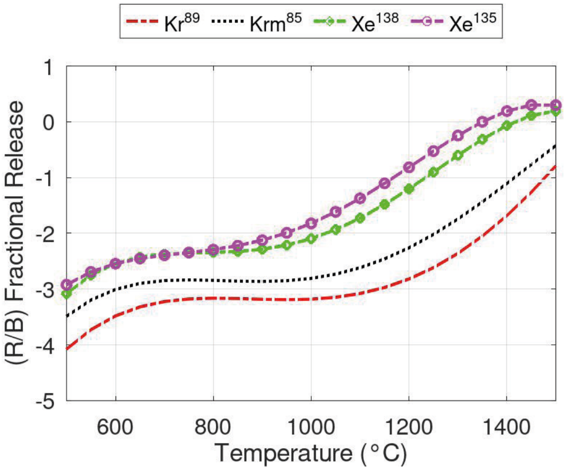

Figure 5. Fission gas release (R/B) measurement was adopted for TRISO particle fuel.

Fission products produced in the kernel, such as noble gases and transition metals, will diffuse to the SiC layer. However, UCO kernels hinder mobility by reducing the ability to transport fission products such as silver and palladium. The temperature and degree of fuel combustion determine the mobility of fission products. Exposure to radiation from the UO_2 kernels produces CO, contributing to the chemical attack on the SiC layer. The reaction between the palladium and the SiC layer affects particle retention and can cause fractures or rapid diffusion.

The SiC layer in FCM fuel contributes to its notable enhanced fission retention capability. Under steady-state conditions, the release rate ratio to birth rate (R/B) represents a numerical measure. Experiments have yielded significant findings, demonstrating substantial gas releases associated with higher burnup, such as ^{85}Kr, ^{137}Cs, and ^{131}I. Krypton is negligible for FIMA, which ranges from 10 to 12% under temperatures of 1600 °C. However, problems occur when reaching 1700 °C. Fission products, carbon monoxide, and dioxide accumulating in the multi-carbon layers could exceed pressure limits during operation.

PyC increases the irradiation creep effect and irradiation-induced dimensional change. When the tensile stress in SiC exceeds its fracture strength, it fails. The standard fuel has TRISO particles and a silicon carbide matrix around a 20% denser uranium-nitride core. The “compact” cladding holds the fuel particles.

Radiation exposure of UO_2 kernels generates CO, which contributes to the chemical attack of the SiC layer. The reaction between the palladium fission product and the SiC layer changes how well the particles stick together and could lead to cracks or fast diffusion. The high fission yield of 239Pu makes actinide burning a critical process that requires meticulous design. Failure of the pyrocarbon layer results in anisotropy and volatile SiO, due to radiation effects. The PyC layer in oxide fuels, which allows gases to pass through, causes high neutron doses.

4 I CONCLUSION

Since the Fukushima Daiichi event, the ATF has researched fuels that can operate at lower temperatures and have lower hydrogen rates. TRIO-matrix fuel is appealing because its ceramics are very corrosion-resistant and have unusually high thermal conductivity. These ceramics also contain many fission products. TRISO represents economic potential and safety for current civilian and upcoming microreactors, including gas-cooled and molten salt-cooled reactors. Over the years, nuclear research centers have fabricated and tested TRIO-coated particle fuel. Under operation, TRSIO accounts for particle-to-particle statistical variations in physical dimensions, such as density and strength properties, arising from fuel fabrication.

The FCM concept describes the double heterogeneity of the SIC surrounding the matrix. Under fuel assembly regulations, designs such as 15 x 15 and 13 × 13 arrays with larger rod diameters but the exact assembly dimensions as commercial ones are permitted. Although the ATF fuel type FCM for PWR has shown superior mechanical performance at high temperatures, it necessitates adaptation for fuel enrichment and manufacturing routes.

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