2026;16(2):67-76. Глобальная ядерная безопасность / Nuclear Safety

https://doi.org/10.26583/gns-2026-02-07
УДК 621.039.5
EDN KZGIEQ
Оригинальная статья / Original paper

Нейтронный анализ устойчивых к авариям материалов топливной оболочки реакторов ВВЭР-1200 с использованием кода SERPENT

Анисур С.К. Рахман
Управление по регулированию атомной энергии Бангладеш (BAERA),
Администрация Бхабан, E-12/A, Агаргаон, Дакка-1207, Бангладеш
✉ *ranisur01@gmail.com*

Аннотация. Разрушение твэлов с циркониевой оболочкой в авариях с потерей теплоносителя (LOCA) в первую очередь вызвано экзотермической реакцией циркония с водяным паром между оболочкой твэла и теплоносителем в реакторах типа ВВЭР, что приводит к образованию взрывоопасного водорода и нарушению целостности оболочки. Повышение безопасности твэлов может быть достигнуто путем замены циркониевой оболочки на материалы толерантного топлива (ATF), которые обладают улучшенной стойкостью к высокотемпературному окислению и пониженным взаимодействием с теплоносителем как в нормальных, так и в аварийных условиях. Авария с потерей теплоносителя является проектной аварией для реакторов ВВЭР, что делает разработку альтернативных материалов оболочки приоритетной задачей для атомных электростанций нового поколения. В данном исследовании с помощью подробного моделирования методом Монте-Карло в коде SERPENT для геометрии реактора ВВЭР-1200 изучается эффективный коэффициент размножения (Keff) стандартных твэлов с циркониевой оболочкой по сравнению с твэлами, использующими три перспективных материала ATF – сплав FeCrAl, композит SiC и сплав NiCr. Результаты демонстрируют значительные различия между материалами: один кандидат проявляет нейтронное поведение, очень близкое к цирконию, с минимальным влиянием на реактивность; другой показывает умеренное, но растущее влияние на протяжении всей кампании; в то время как третий демонстрирует существенное влияние на реактивность, которое потребовало бы серьезного изменения конструкции активной зоны. Эти количественные результаты подтверждают перспективность отдельных материалов ATF в качестве замены циркония, способствуя снижению рисков окисления, исключению образования водорода и уменьшению вероятности аварий на ядерных реакторах при сохранении приемлемых нейтронно-физических характеристик. Расчеты выполнены специально для атомной электростанции с реактором ВВЭР-1200 и предоставляют необходимые данные для выбора материалов и оптимизации проектирования активной зоны.

Ключевые слова: аварии с потерей теплоносителя (LOCA), оболочка реактора, реактор ВВЕР-1200, эффективный коэффициент размножения (Keff), топливо, устойчивое к авариям (ATF)

Для цитирования: Анисур С.К. Рахман. Нейтронный анализ устойчивых к авариям материалов топливной оболочки реакторов ВВЭР-1200 с использованием кода SERPENT. *Глобальная ядерная безопасность.* 2026;16(2):67-76. https://doi.org/10.26583/gns-2026-02-07

For citation: Anisur S.K. Rahman. Neutronic analysis of accident-tolerant fuel cladding materials for VVER-1200 reactors using the SERPENT code. *Nuclear Safety.* 2026;16(2):67-76. (In Russ.). https://doi.org/10.26583/gns-2026-02-07

Neutronic analysis of accident-tolerant fuel cladding materials for VVER-1200 reactors using the SERPENT code

Anisur S.K. Rahman
Bangladesh Atomic Energy Regulatory Authority (BAERA), Authority Bhaban, E-12/A, Agargaon,
Dhaka-1207, Bangladesh
✉ *ranisur01@gmail.com*

Abstract. The failure of zirconium (Zr) fuel elements in Loss-of-Coolant Accidents (LOCAs) is primarily caused by the exothermic zirconium-steam reaction between the Zr fuel cladding and coolant water in VVER-type reactors, which generates explosive hydrogen gas and compromises cladding integrity. Enhancing fuel element safety can be achieved by replacing the Zr cladding with Accident Tolerant Fuel (ATF) materials that exhibit improved high-temperature oxidation resistance and reduced interaction with coolant under both normal and emergency conditions. LOCA is a design basis accident for VVER reactors, making the development of alternative cladding materials a priority for next-generation nuclear power plants. This study investigates the effective multiplication coefficient (Keff) of standard Zr-clad fuel rods compared to those with three candidate ATF cladding materials – FeCrAl alloy, SiC composite, and NiCr alloy–using detailed Monte Carlo simulations with the SERPENT code for the VVER-1200 reactor geometry. The results demonstrate significant differences among the materials: one candidate exhibits neutronic behavior very close to zirconium with minimal reactivity control, another shows a moderate but increasing penalty throughout the burnup cycle, while the third displays a substantial reactivity control that would necessitate major core redesign. These quantitative findings highlight the promise of select ATF materials as replacements for Zr, contributing to reduced oxidation risks, elimination of hydrogen generation, and decreased accident probabilities in nuclear reactors while maintaining acceptable neutronic performance. The calculations are specifically performed for the WWER-1200 nuclear power plant and provide essential data for material selection decisions and core design optimization.

Keywords: Loss-of-Coolant Accidents (LOCA), Cladding, WWER-1200 reactor, Effective multiplication coefficient (Keff), Accident Tolerant Fuel (ATF)

1. Introduction

Accident Tolerant Fuel (ATF) is designed to endure loss-of-cooling scenarios in a reactor core for extended durations compared to traditional zirconium (Zr) cladding fuel. By enhancing the safety margins of nuclear power plants, ATF contributes to improved operational efficiency through long-life fuel, supports the current nuclear power plant fleet, facilitates the licensing of advanced reactor technologies, and reduces operational and maintenance costs[1,2,3], ultimately benefiting consumers through lower electricity costs. The 2011 Fukushima Daiichi nuclear accident served as a stark reminder of the vulnerabilities associated with conventional zirconium-based (Zr) fuel cladding materials under extreme conditions, particularly in Loss-of-Coolant Accidents (LOCAs). During such accidents, Zr reacts with steam at elevated temperatures, generating hydrogen gas–a key factor in hydrogen explosions that exacerbated the severity of the Fukushima disaster. Although much attention has been given to this event, the challenges with Zr cladding extend beyond this high-profile incident. Its chemical reactivity and susceptibility to rapid oxidation under accident conditions remain critical areas of concern for modern nuclear reactors. This underscores the urgent need for alternative cladding materials, especially for advanced reactor designs such as the VVER-1200, which operate with unique neutronic and thermal characteristics. The VVER-1200, as a Generation III+ reactor, benefits significantly from the incorporation of Accident Tolerant Fuel (ATF) materials. These materials–such as FeCrAl, SiC, and NiCr–address the limitations of Zr cladding by offering superior resistance to high-temperature oxidation and reduced hydrogen production during LOCA scenarios. Moreover, the inclusion of ATF materials enhances fuel burnup, reactivity control, and safety margins, ensuring improved performance and resilience under both normal and accident conditions [1,2].

This study leverages the SERPENT Monte Carlo code to perform a detailed neutronic analysis of the multiplying coefficient characteristics of ATF materials in a VVER-1200 reactor core. By evaluating the safety and operational benefits of these materials, the research highlights their potential to mitigate the risks associated with Zr cladding while aligning with the safety objectives of next-generation nuclear power plants. The findings not only address the legacy challenges underscored by past accidents but also pave the way for safer, more efficient

---

[1] IAEA. Accident Tolerant Fuel Concepts for Light Water Reactors. IAEA TECDOC Series, No. 1797. Vienna: *International Atomic Energy Agency*. 2015. Available at: https://www-pub.iaea.org/MTCD/Publications/PDF/TE1797web.pdf (accessed: 01.02.2026)

[2] World Nuclear News. (2023, March). First Framatome ATF fuel loaded at US reactor. Available at: https://world-nuclear-news.org/ (accessed: 01.02.2026)

[3] OECD Nuclear Energy Agency. JANIS Online version. Available at: https://www.oecd-nea.org/janis/ (accessed: 01.02.2026)

nuclear fuel technologies tailored to advanced reactor designs [3,4].

2. Short Description of the SERPENT Program

The SERPENT code is a state-of-the-art Monte Carlo neutron transport simulation tool primarily written in ANSI-C programming language. Initially developed for the Linux operating system, SERPENT has also been successfully compiled and tested on macOS and various UNIX-based systems.

The Monte Carlo method, which underpins SERPENT's computational framework, relies on probabilistic techniques for solving neutron transport equations. This approach is computationally intensive, and the efficiency of calculations is directly influenced by the available processing power.

SERPENT was originally designed as a simplified neutron transport code for reactor physics applications, with an emphasis on usability and reduced computational overhead. Over time, it has evolved to include advanced capabilities, such as burnup calculations for reactor fuel analysis.

Today, SERPENT is utilized in a wide range of applications, including:

- Generating group constants for deterministic reactor physics codes.
- Modeling and simulation of coupled multi-physics systems.
- Detailed studies of nuclear reactor core designs and materials.

Its versatility and efficiency have made SERPENT a valuable tool in nuclear engineering research and development.

3. Description of the Calculation Model

The fuel rod geometry used in this study is based on the VVER-1200 reactor design and is divided into five distinct zones, each with a specific radius and material composition (Fig. 1):

Zone 1: Helium Gas Gap

Radius: 0.1 cm.

Material: Helium gas, used as a buffer layer to accommodate thermal expansion and maintain structural integrity.

Zone 2: Fuel Region

Radius: 0.39 cm.

Material: Uranium dioxide (U^{235}) as the fissile material. This zone contains the fuel that undergoes nuclear fission.

Zone 3: Clearance Gap

Material: A small clearance region to account for thermal and mechanical expansion during operation.

Zone 4: Cladding

- Inner Radius: 0.395 cm.
- Outer Radius: 0.455 cm.
- Thickness: 0.06 cm.
- Material: Different types of cladding materials are analyzed for their performance under operational and accident conditions. It is important to note that this study considers a complete replacement of the standard Zirconium alloy cladding (E110) with a monolithic layer of the candidate ATF material (FeCrAl alloy, SiC composite, or NiCr alloy). The modeling of thin protective coatings on a Zirconium substrate, which presents a more complex heterogeneous structure requiring different computational approaches, is beyond the scope of this investigation and is planned for future work.

The material compositions and densities are:

- **Zr (reference):** E110 alloy (Zr-1%Nb), density 6.55 g/cm³
- **FeCrAl alloy:** Composition: Fe-13Cr-5Al (wt.%), density 7.1 g/cm³
- **SiC composite:** Stoichiometric SiC, density 3.21 g/cm³ (fully dense)
- **NiCr alloy:** Composition: Ni-20Cr (wt.%), density 8.4 g/cm³

Zone 5: Coolant Zone

Material: Water, serving as both a coolant and a neutron moderator to sustain the fission chain reaction.

This multi-zone model reflects the detailed structure of a VVER-1200 fuel rod and provides the basis for evaluating the neutronic characteristics and thermal performance of various cladding materials. The calculations performed in this study assess the impact of these materials on the multiplying coefficient and other critical reactor safety parameters [5,6,7].

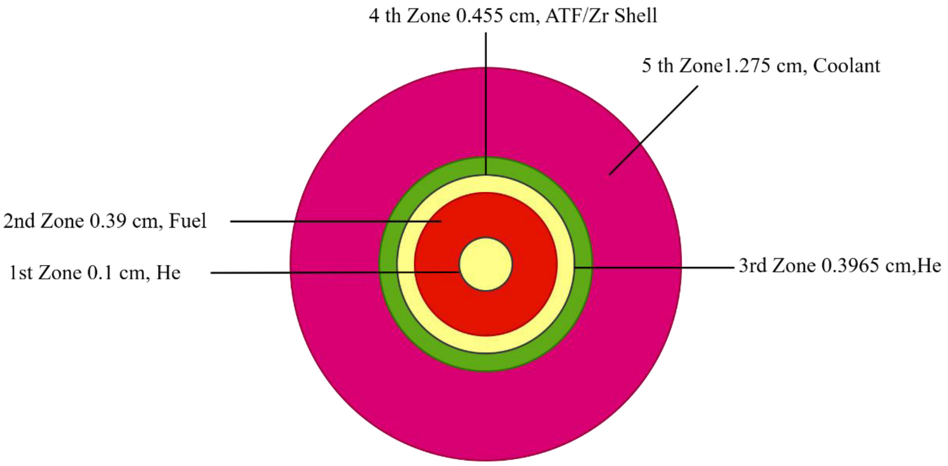

Figure 1. Fuel rod including ATF cladding materials[4]

4. Configuration and main characteristics of the VVER-1200 core

The fuel assembly of the VVER-1200 reactor is an advanced design optimized for safety, fuel efficiency, and operational longevity. Its structure includes the following components in figure 2:

1. 285 Fuel Cells (UO2):

These cells contain uranium dioxide (UO_2) fuel pellets.

The primary driver of the fission reaction, responsible for generating heat for electricity production.

2. 27 Fuel Cells with Gadolinium (Burnable Absorbers):

These cells incorporate gadolinium (Gd) as a burnable neutron absorber.

Gadolinium helps manage excess reactivity at the beginning of the fuel cycle and ensures a more uniform burn-up of fuel over time.

3. 18 Guide Tube Cells:

These cells house guide tubes for control rods.

The control rods are used for reactivity regulation, providing both operational control and emergency shutdown capabilities.

4. 1 Central Tube Cell:

Located at the center of the assembly, typically used for instrumentation or coolant flow optimization.

The key characteristics of the VVER-1200 reactor core are presented in Table 1.

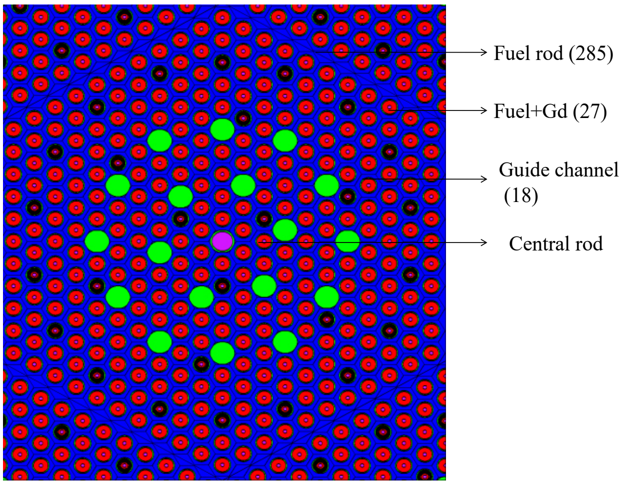

Figure 2. Fuel Assembly

---

[4] It is important, that the analysis considers a complete replacement of the standard Zirconium alloy cladding with FeCrAl, SiC, and NiCr ATF material. The modeling of thin protective coatings on a Zirconium substrate, which presents a more complex heterogeneous structure, is beyond the scope of this study and is planned for future work.

Table 1. Core composition of VVER-1200 reactor

Parameter Name	Value
Reactor thermal power (MWt)	3200
Reactor electrical power (MWt)	1200
Number of fuel assembly in the core	163
Coolant temperature at the reactor inlet (˚C)	298 ± 2.5
Average coolant temperature at the reactor outlet (˚C)	329 ± 5.0
Active core diameter (cm)	316
Active core height (cm)	375
Refueling frequency (months	12 (18)
Primary coolant temp. at core inlet (˚C)	298.2
Primary coolant temp. at core outlet (˚C)	328.9
Primary coolant pressure at reactor vessel outlet (MPa)	16.2
Feed water temperature at SG inlet (˚C)	225
Assembly Fuel assembly form	Hexagonal
Number of fuel rod in the fuel assembly	312
Fresh fuel assembly enrichment	1.6%, 2.4%, 3.6%,4.95%
Fuel rod pitch (mm)	12.75
The number of fuel rods, material, internal and external diameter of the cladding of the fuel rod accordingly	285, Alloy E110,$7.80\cdot10^{-3}$ m, $9.10\cdot10^{-3}$ m
Number of tegs (fuel+Gd), material, internal and external diameter of the cladding of the tegs (fuel+ Gd) rod accordingly	27, Alloy E110,$7.80\cdot10^{-3}$ m, $9.10\cdot10^{-3}$ m
The internal diameter of the cladding of a fuel rod / teg (Fuel+Gd)	$7.93\cdot10^{-3}$ m
Fuel enrichment of tegs, ^{235U}, вес. %	4.0
Content Gd_2O_3, вес. %	8
Lattice pitch of fuel elements,	$12.75\cdot10^{-3}$ m
Guide channel: Its materials, internal and external diameter accordingly	Alloy E635, $13.0\cdot10^{-3}$m, $11.0\cdot10^{-3}$m
Central rod: Its materials, internal and external diameter accordingly	Alloy E635, $13.0\cdot10^{-3}$m, $11.0\cdot10^{-3}$m

5. Discussion on Accident Tolerant Fuel (ATF) Materials

Accident Tolerant Fuel refers to nuclear fuel and cladding materials that enhance the safety and efficiency of nuclear reactors, particularly under accident conditions, such as loss of coolant accidents (LOCA). Accident Tolerant Fuel (ATF) cladding materials, such as NiCr, SiC, and FeCrAl, have been proposed as alternatives or enhancements to conventional zirconium (Zr) cladding. These materials aim to improve the performance and safety of nuclear power plants under both normal operation and accident conditions.

Zirconium, while commonly used for fuel cladding due to its excellent neutron transparency, is chemically active at elevated temperatures. It reacts with water vapor at temperatures above 500–600°C, and at temperatures exceeding 900°C, this reaction becomes highly exothermic, producing significant amounts of hydrogen. The reaction can be represented as: $Zr+2H_2O\rightarrow ZrO_2+2H_2$.

This reaction poses a severe risk as it can lead to cladding failure and hydrogen explosions. To mitigate these risks, alternative cladding materials are needed to reduce oxidation and improve thermal stability, ensuring safe operation of nuclear power plants under both normal and accident conditions.

5.1 Zirconium Alloy with Chromium Coating

Zirconium cladding with chromium coatings has gained significant attention due to chromium's thermodynamic and corrosion-resistant properties. While Zr forms a highly durable ZrO layer at high temperatures, it undergoes phase transformations above certain thresholds, weakening its structural integrity. Chromium oxide (Cr_2O_3) forms a robust barrier to oxygen diffusion, which helps to mitigate oxidation and hydrogen generation.

Advantages of Chromium Coatings:

– **High Melting Point**: Improves resilience under high-temperature conditions.

– **Corrosion Resistance**: Performs well in superheated water environments, withstanding temperatures up to 1000°C.

– **Thermal Conductivity**: Enhances heat dissipation, reducing thermal stress.

Due to these properties, many nuclear power-producing nations have begun implementing chromium-coated cladding materials for advanced reactor designs.

5.2 Silicon Carbide (SiC) Composites

Silicon Carbide (SiC) is another promising ATF cladding material due to its exceptional high-temperature strength, stability under irradiation, and lower oxidation rates compared to Zr. SiC remains stable in water vapor environments at temperatures up to 1200°C and has superior material properties, including [9,10]:

– **Melting Point**: 2800°C, providing high thermal resilience.

– **Thermal Conductivity**: 25 W/m·K, ensuring effective heat transfer.

– **Irradiation Stability**: Maintains structural integrity under neutron exposure.

For the ATF**,** FeCrAl, SiC, and NiCr alloys each offer significant advantages over Zr cladding materials, especially in terms of safety during accident scenarios.

– FeCrAl alloys provide superior oxidation resistance and hydrogen management, which are crucial for preventing accidents such as hydrogen explosions. However, their neutron absorption properties require careful reactor design consideration [8].

– SiC composites outperform Zr in high-temperature stability and oxidation resistance and do not produce hydrogen, making them a highly promising candidate for accident-tolerant cladding. However, their mechanical brittleness and fabrication challenges are potential drawbacks[5].

– NiCr alloys share some similarities with FeCrAl but are typically less studied in the context of ATF. They may provide comparable oxidation resistance, but like FeCrAl, they can affect reactivity due to their neutron absorption characteristics.

6. Result Calculation by the SERPENT Program

Among the various Accident Tolerant Fuel (ATF) cladding options, FeCrAl alloys have emerged as a promising candidate for next-generation nuclear reactors. FeCrAl alloys typically contain 10-15 wt.% chromium (Cr) and 3-6 wt.% aluminum (Al). These alloys exhibit exceptional resistance to high-temperature oxidation due to the formation of a protective chromium oxide (Cr_2O_3) layer, which is stable up to temperatures around 1000°C. At temperatures above 1000°C, the chromium oxide layer is replaced by a more durable aluminum oxide (Al_2O_3) layer. The dense Al_2O_3 layer serves as an effective barrier against oxidizing species, including O^{2-}, OH^-, and H_2O_2, thereby preventing further oxidative degradation of the material.

One of the key advantages of FeCrAl alloys, especially with the Al_2O_3 protective layer, is their significantly reduced hydrogen permeability. Studies have shown that the Al_2O_3 layer reduces hydrogen permeation by a factor of three when compared to the oxidized FeCrAl material. In contrast, the zirconium-based (Zr) cladding currently used in nuclear reactors is prone to significant hydrogen absorption. When Zr reacts with hydrogen, zirconium hydrides (ZrH_2) are formed, which migrate to the outer surface of the cladding. This migration reduces the mechanical properties of the cladding, such as the fracture toughness and fatigue resistance. Thus, the stable oxide layer in FeCrAl alloys provides a significant advantage in hydrogen management compared to Zr alloys, which form brittle hydride phases.

Using the SERPENT code, the effective multiplication coefficient (Keff) was calculated as a function of burnup time for fuel rods with different cladding materials. Burnup calculations were performed up to 500 effective full power days, corresponding to a fuel burnup of approximately 40-45 MWd/kgU. Table 2 presents the calculated Keff values with their associated statistical errors.

---

[5] IAEA. (2020). Accident Tolerant Fuel Concepts for Light Water Reactors (ATF-TM-2). Proceedings of a Technical Meeting held in Moscow, Russian Federation, 2019. IAEA-TECDOC-1921. Available at: https://www.iaea.org/publications/10972/accident-tolerant-fuel-concepts-for-light-water-reactors (accessed: 01.02.2026)

Table 2. Effective Multiplying Coefficient (Keff) with statistical error for the Zr alloy and Zirconium (Zr) coated with FeCrAl,NiCr and SiC repectively are calculated by using the SERPENT program

Burnup (Days)	Alloy Zr (Reference) Effective Multiplying Coefficient (Keff) with Error	Alloy (Zr+FeCrAl) Effective Multiplying Coefficient (Keff) with Error	Alloy (Zr+SiC) Effective Multiplying Coefficient (Keff) with Error	Alloy (Zr+NiCr) Effective Multiplying Coefficient (Keff) with Error
0	1.33567 ± 0.00042	1.30383 ± 0.00044	1.32645 ± 0.00043	1.19550 ± 0.00048
50	1.35175 ± 0.00041	1.30429 ± 0.00043	1.34535 ± 0.00042	1.20763 ± 0.00047
100	1.36357 ± 0.00040	1.28874 ± 0.00045	1.35482 ± 0.00041	1.20808 ± 0.00047
150	1.34702 ± 0.00042	1.26717 ± 0.00046	1.33484 ± 0.00042	1.18587 ± 0.00048
200	1.32290 ± 0.00043	1.24125 ± 0.00047	1.31956 ± 0.00043	1.15958 ± 0.00049
250	1.30366 ± 0.00044	1.21555 ± 0.00048	1.29477 ± 0.00044	1.13095 ± 0.00050
300	1.28041 ± 0.00045	1.18902 ± 0.00049	1.26769 ± 0.00045	1.09880 ± 0.00051
450	1.21590 ± 0.00047	1.11726 ± 0.00052	1.20659 ± 0.00046	1.02288 ± 0.00054
500	1.13523 ± 0.00050	1.02648 ± 0.00055	1.12443 ± 0.00048	0.928448 ± 0.00058

To quantify of the reactivity degradation associated with each ATF material, the relative change in the effective multiplication factor (ΔKeff) compared to the reference Zirconium cladding was calculated at the beginning of life (0 burnup days) and after 500 days. The results are summarized in Table 3, with errors propagated from the Monte Carlo statistics.

Table 3. Relative change in Keff compared to Zirconium cladding with propagated errors

Material	ΔKeff at 0 days	ΔKeff at 500 days
FeCrAl	-2.38% ± 0.05%	-9.58% ± 0.08%
SiC	-0.69% ± 0.04%	-0.95% ± 0.06%
NiCr	-10.49% ± 0.06%	-18.22% ± 0.09%

The analysis shows that SiC has the closest neutronic behavior to Zirconium, with a minimal reactivity (less than 1% throughout the cycle). FeCrAl demonstrates a moderate reactivity, which increases with burnup. NiCr, however, exhibits a severe reactivity reduced (over 10% at BOL), rendering it less attractive from a neutronic perspective without significant core design modifications to compensate for the reactivity loss.

The results presented here graphically, which provides a detailed neutronic analysis of the FeCrAl alloys and their performance within the reactor core. The relationship between the multiplying coefficient and burnup in a VVER reactor (or any other nuclear reactor) is typically inverse. This means that as burnup increases, the multiplying coefficient (which represents the reactor's reactivity) decreases over time. This decrease occurs because, as the reactor operates, fissile isotopes are consumed through nuclear fission. The depletion of these isotopes reduces the number of available fissile nuclei for neutron-induced fission reactions, leading to a decline in the multiplication factor. In the case of Accident Tolerant Fuel (ATF) materials like FeCrAl and SiC, burnup can increase significantly, reaching values of up to 80 MWd/kgU.These findings, highlight the improved safety and material performance of FeCrAl,SiC, NiCr alloys, positioning them as viable alternatives for the next generation of nuclear fuel cladding materials.

The errors in all calculations are very small (within ±0.0006), which is about ±0.04-0.06% (Tab. 2) in relative terms. This means the results are very precise, shown in figure 3.

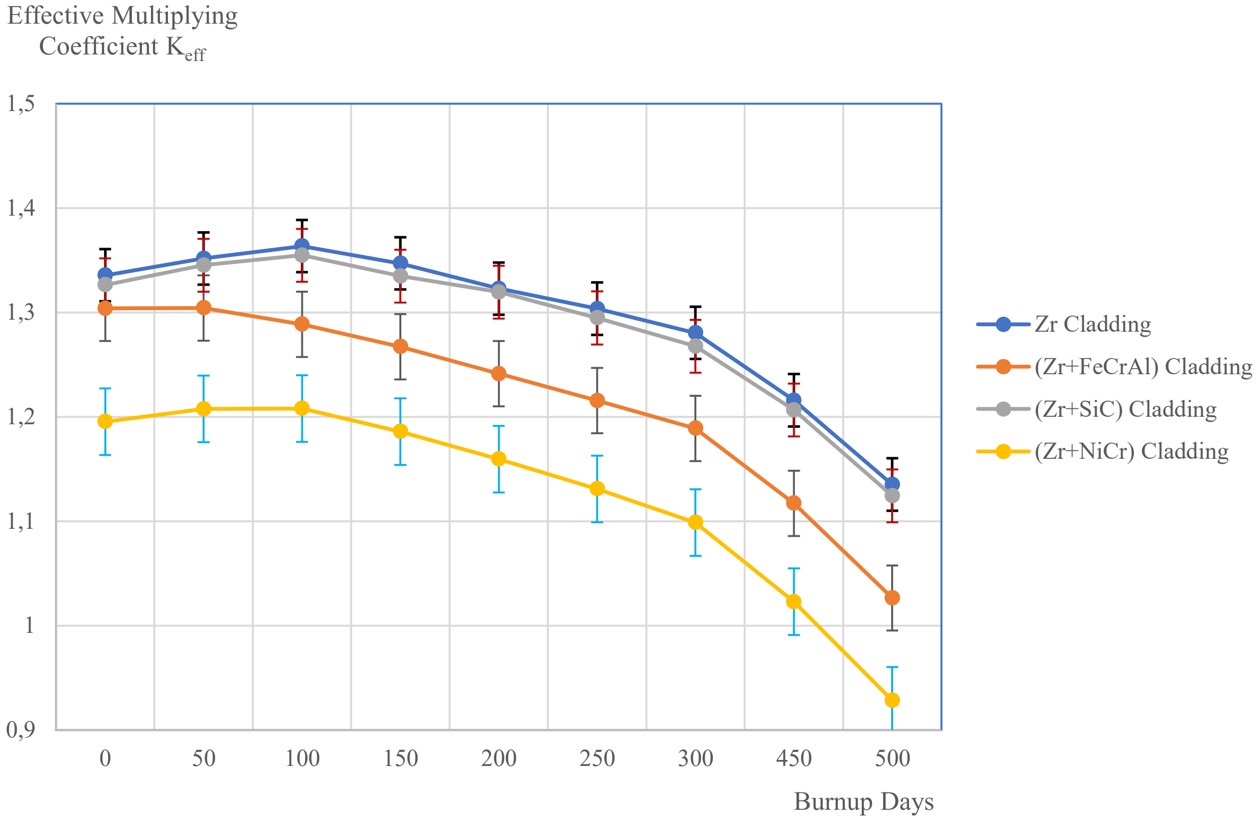

Figure 3. Multiplying Coefficient vs Burnup time for Accident Tolerant Fuel (ATF) materials with error bands

7. Result Analysis on Accident Tolerant Fuel (ATF)

7.1 Neutronic Performance and Reactivity degradation

The calculated Keff values presented in Table 2 clearly demonstrate a reactivity degradation associated with ATF cladding materials relative to reference Zr cladding.

At beginning of cycle (0 days burnup):

Zr: 1.33567

Zr+SiC: 1.32645 → ΔK ≈ −0.009 (≈ −670 pcm)

Zr+FeCrAl: 1.30383 → ΔK ≈ −0.032 (≈ −2400 pcm)

Zr+NiCr: 1.19550 → ΔK ≈ −0.140 (≈ −10,500 pcm)

The observed trend directly correlates with the microscopic thermal neutron absorption cross-sections of the cladding materials:

Zr ≈ 0.18 barns

SiC (effective) ≈ very low absorption (Si and C both weak absorbers)

FeCrAl ≈ ~2–3 barns (Cr and Fe contribution)

NiCr → significantly higher absorption due to Ni (~4.5 barns)

SiC demonstrates the smallest reactivity rediced because both silicon and carbon have low absorption cross-sections and therefore minimally perturb the neutron economy of the lattice. NiCr exhibits the largest reduction in Keff due to the relatively high microscopic absorption cross-section of nickel, leading to increased parasitic neutron absorption and reduced multiplication. FeCrAl shows intermediate behavior, consistent with its moderate absorption characteristics. Thus, the neutronic performance ranking based on calculated data is:

SiC → FeCrAl → NiCr

This ranking is directly supported by the quantitative SERPENT results.

7.2 Implications for Fuel Cycle and Core Design

The reduction in K_{eff} directly affects excess reactivity and therefore impacts fuel cycle length and core design strategy.

For FeCrAl and especially NiCr, the reactivity degradation would:

- Reduce initial excess reactivity.
- Shorten achievable fuel cycle length under fixed enrichment.
- Require compensation through:
  - Increased ^{235}U enrichment,
  - Reduced burnable absorber (Gd_2O_3) loading,
  - Modified fuel assembly design.

In contrast, SiC introduces only a minor reactivity degradation, which could likely be compensated within standard enrichment margins without major design modification. The substantial reactivity degradation observed for NiCr (~10,000 pcm at BOC) suggests that its implementation in WWER-1200 would require substantial redesign of enrichment zoning and burnable absorber distribution, potentially affecting economic performance.

Therefore, from a neutronic perspective:

- SiC appears most compatible with existing WWER-1200 core design.
- FeCrAl may be feasible with moderate design adjustments.
- NiCr presents significant neutronic challenges.

7.3 Error Analysis

The statistical errors in the Monte Carlo calculations are sufficiently small to resolve the differences between materials. The 95% confidence intervals for the reactivity penalties are:

- FeCrAl at 0 days: ±0.10% (relative penalty clearly distinguishable from zero)
- SiC at 0 days: ±0.08% (penalty small but statistically significant)
- NiCr at 0 days: ±0.12% (penalty clearly significant)

The small error ranges show that the ranking of the materials is reliable and not caused by random statistical variation.

8. Conclusion

This work presents a consistent Monte Carlo–based neutronic comparison of zirconium and three ATF cladding options for a VVER-1200 lattice cell under identical geometric, material, and burnup conditions. The novelty of the study lies in the direct quantification of the reactivity degradation introduced by each candidate material within a unified SERPENT modeling framework. The calculations demonstrate that the magnitude of Keff reduction is primarily governed by the microscopic absorption cross-sections of alloying elements, particularly nickel and chromium. The results show that:

1. The neutronic impact of SiC is minimal and remains within typical operational reactivity margins across the burnup range considered. SiC has the best neutronic performance. It causes only a small reactivity loss (less than 1%), so it could replace Zr without major design changes.
2. FeCrAl produces a systematic and burnup-dependent reactivity suppression that would require compensatory core design measures. It causes a moderate and increasing reactivity loss (about 2-10%). It may require slightly higher fuel enrichment or design adjustments.
3. NiCr causes a substantial parasitic absorption effect, leading to a reactivity loss that exceeds practical compensation limits under standard enrichment assumptions for VVER-1200. It has very poor neutronic performance. It causes large reactivity loss (over 10-18%) and would need major core redesign.

The study confirms that the choice of ATF cladding involves a trade-off between enhanced accident tolerance and neutronic performance. The quantitative results obtained for the VVER-1200 provide a necessary basis for more comprehensive multi-physics optimizations, where the identified reactivity penalties must be balanced against the significant safety gains in oxidation resistance and hydrogen reduction offered by these materials. The errors are very small (±0.04-0.06%), so the material comparison is reliable and statistically significant.

REFERENCES

1. Alhmoud A.Z., Kruglov V.B., Kruglov A.B., Tanash, H.A. Tolerant fuel for VVER reactors. *Journal of Physics: Conference Series*, 2020;1689 012069. https://doi.org/10.1088/1742-6596/1689/1/012069

2. Yadav K.K., Pal, U., & Karthikeyan, R. Concept of accident tolerant fuel in nuclear reactors. *Nuclear and Particle Physics Proceedings*, 2023;341:62-66. https://doi.org/10.1016/j.nuclphysbps.2023.09.026

3. Zinkle S.J., Terrani, K. A., Gehin, J. C., Ott, L. J., & Snead, L. L. Accident tolerant fuels for LWRs: A perspective. *Journal of Nuclear Materials*. 2014:448(1-3):374-379. https://doi.org/10.1016/j.jnucmat.2013.12.005

4. Terrani K.A. Accident tolerant fuel cladding development: Promise, status, and challenges. *Journal of Nuclear Materials*. 2018;501:13-30. https://doi.org/10.1016/j.jnucmat.2017.12.043

5. Anisur, R. S. K., & Uvakin, M. A. Uncertainty analysis in the physical calculation of VVER cells in the daily maneuvering schedule. *Journal of Physics: Conference Series*, 2018;1133 012048. https://doi.org/10.1088/1742-6596/1133/1/012048

6. Rahman A.S.K., & Uvakin, M. A. Compare the Result of Uncertainty Analysis in the Physical Calculations of WWER Cells in the Daily Maneuvering Schedule by GETERA and WIMS Programs. *Global Nuclear Safety*, 2019;1(30):90-100. Available at: http://gns.mephi.ru/sites/default/files/journal/file/en.2019.1.3.2.pdf (accessed: 01.02.2026)

7. Rahman A.S.K., Uvakin M.A. Investigation of the power peaking factor Kq in the fuel assembly during the maneuvering mode of the VVER-1000 reactor. *Journal of Physics: Conference Series*. 2020;1689 012029. https://doi.org/10.1088/1742-6596/1689/1/012029

8. Lance L Snead, Takashi Nozawa, Yutai Katoh, Thak-Sang Byun, Sosuke Kondo, David A. Petti. Handbook of SiC properties for fuel performance modeling. Journal of Nuclear Materials. 2007;371(1-3):329-377. https://doi.org/10.1016/j.jnucmat.2007.05.016

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ:
Работа выполнена без дополнительных источников финансирования

КОНФЛИКТ ИНТЕРЕСОВ:
Автор заявляет об отсутствии конфликта интересов.

ИНФОРМАЦИЯ ОБ АВТОРЕ:
Анисур С.К. Рахман, старший научный сотрудник, Управление по регулированию атомной энергии Бангладеш (БАЭРА), Агаргаон, Дакка-1207, Бангладеш.
https://orcid.ord/0000-0001-7803-8234
WosResearher ID: D-3381-2019
e-mail: ranisur01@gmail.com

FUNDING:
No additional funding.

CONFLICT OF INTEREST:
The author declare no conflict of interest.

INFORMATION ABOUT THE AUTHOR:
Anisur S.K. Rahman, Senior Scientific Officer (SSO) Bangladesh Atomic Energy Regulatory Authority (BAERA), Authority Bhabon, E-12/A, Agargaon, Dhaka-1207, Bangladesh.
https://orcid.ord/0000-0001-7803-8234
WosResearher ID: D-3381-2019
e-mail: ranisur01@gmail.com

Поступила в редакцию / Received 01.02.2026
После доработки / Revision 06.04.2026
Принята к публикации / Accepted 09.04.2026