FISA EURADWASTE 2025

SNETP Forum

Neutronic Analysis of Accident Tolerant Fuel Concepts in Spectral Shift Regulation Condition

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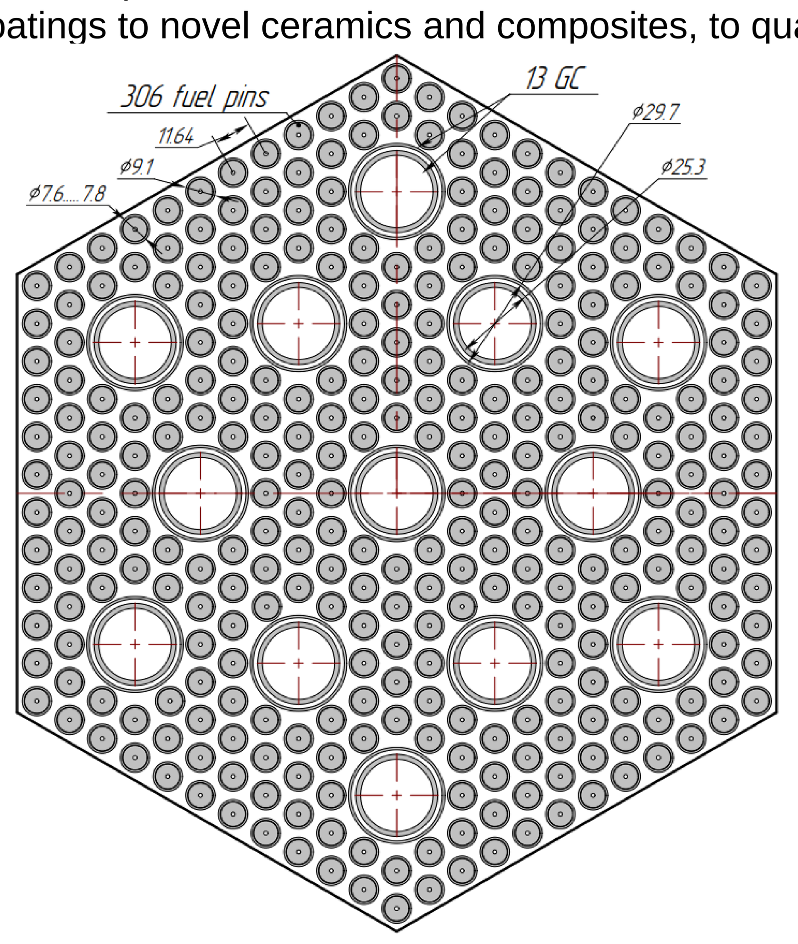
1. Introduction

The Fukushima Daiichi accident in 2011 stimulated worldwide research into accident-tolerant fuel (ATF) for light-water reactors. ATF concepts aim to maintain equal or better performance than conventional UO_2–Zr fuel during normal operation while significantly improving safety margins under accident conditions. Improved accident performance is generally interpreted as increased coping time for operators to respond – for example, fuels and claddings that resist oxidation and overheating longer, delaying core damage. In response, international efforts have investigated advanced fuel and cladding materials for pressurized water reactors (PWRs). Over the 2011–2025 period, numerous experimental and computational studies have evaluated candidate ATF materials, from enhanced Zr alloys and coatings to novel ceramics and composites, to quantify their neutronic behavior and safety benefits [1].



In parallel, researchers have revisited spectral shift regulation (SSR) techniques—an approach to reactor operation that intentionally hardens the neutron spectrum during part of the fuel cycle—to extend fuel utilization and manage reactivity in high-performance cores, offering total exception of burnable poisons such as gadolinium and erbium, and boron acid diluted in the coolant.

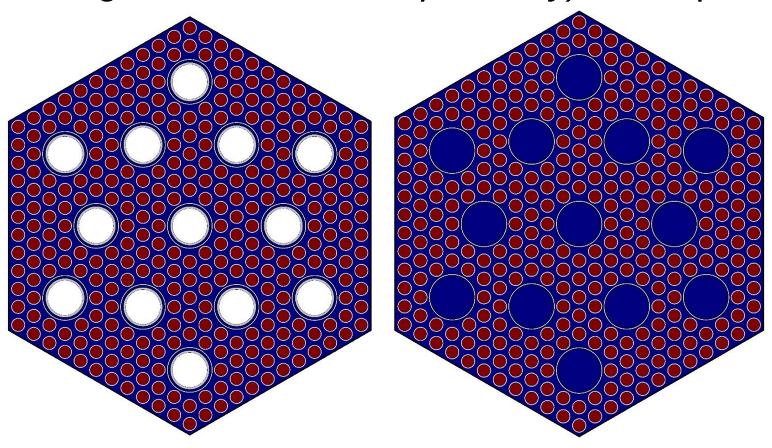
There are two main methods of SSR:

I. controlling the concentration of light water and heavy water in the coolant [2];
II. adjusting the water uranium ratio (WUR) using mechanical displacers [3].

This study provides a neutronic analysis of ATF concepts under spectral shift conditions, with an emphasis on PWR applications employing mechanical displacers. For this, polycell structure of the reference model of the modified fuel assembly of PWR reactor used.

2. Methodology

- GETERA deterministic code is used for neutronics simulations. Calculation is carried out in the method of probabilities of the first collisions based on the BNAB library [4].
- The selected assembly-level polycell structure undergoes burnup calculations under constant power mode for both with and without mechanical displacers (*see the figure left: white gaps and right: blue-water, respectively*) over specified time intervals.



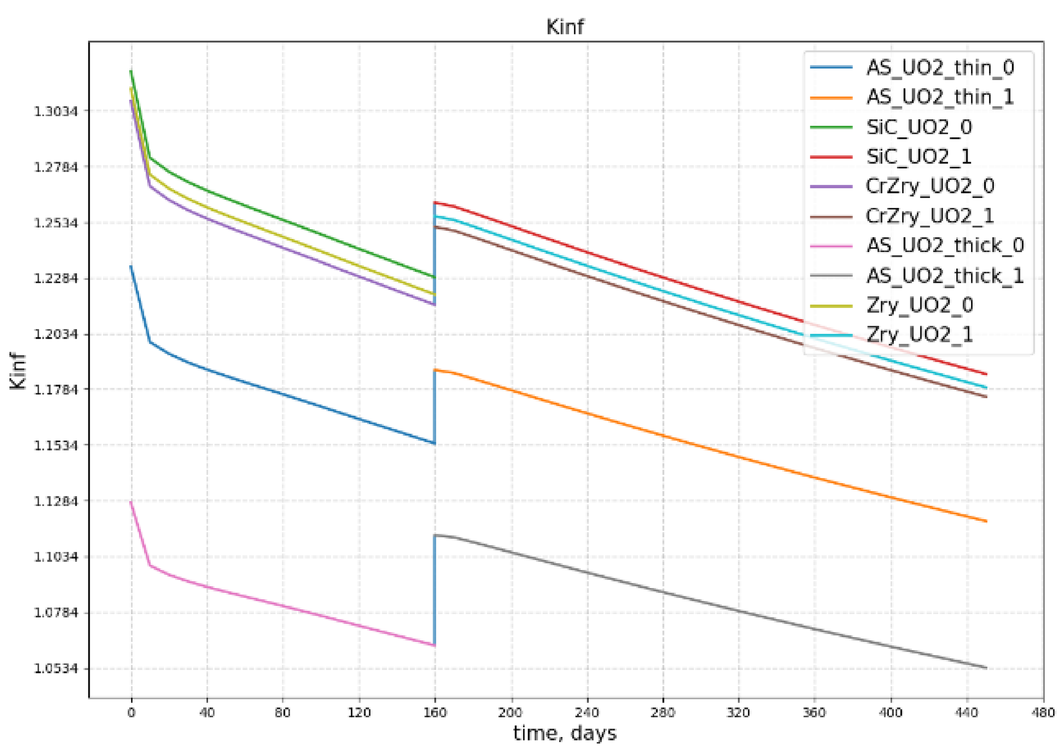
Fuel type	WUR with displacers	WUR without displacers
UO_2	1.51	1.98
U3Si2	1.28	1.68
UN	1.07	1.41

Material compositions:

- Advanced Steel (AS): A FeCrAl alloy (APMT) with the composition Fe–21Cr–5Al–3Mo (wt%);
- Chromium-Coated Zirconium Alloy (CrZry): Features a chromium coating up to 20 µm thick;
- Silicon Carbide (SiC);
- Uranium Dioxide (UO_2);
- Uranium Nitride (UN);
- Uranium Silicide (U_3Si_2).

Claddings	Fuels
CrZry	UO_2
FeCrAl	U_3Si_2
SiC	UN

3. Results

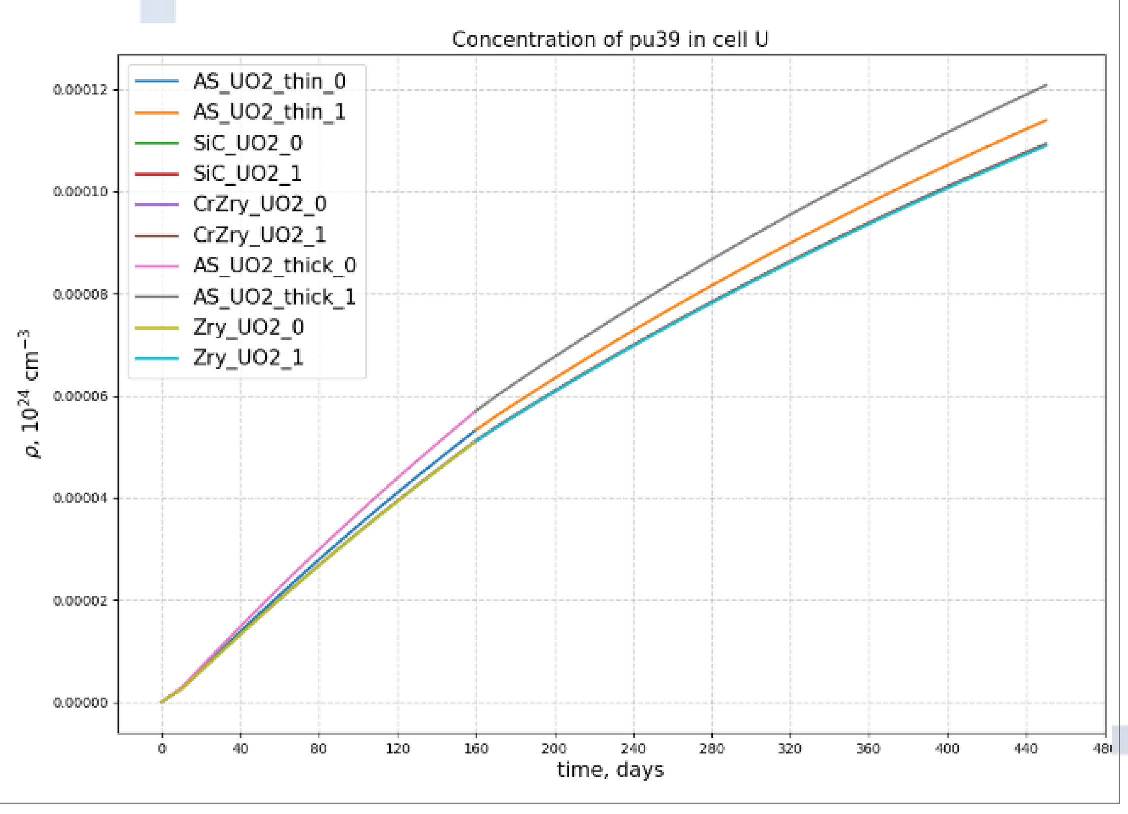


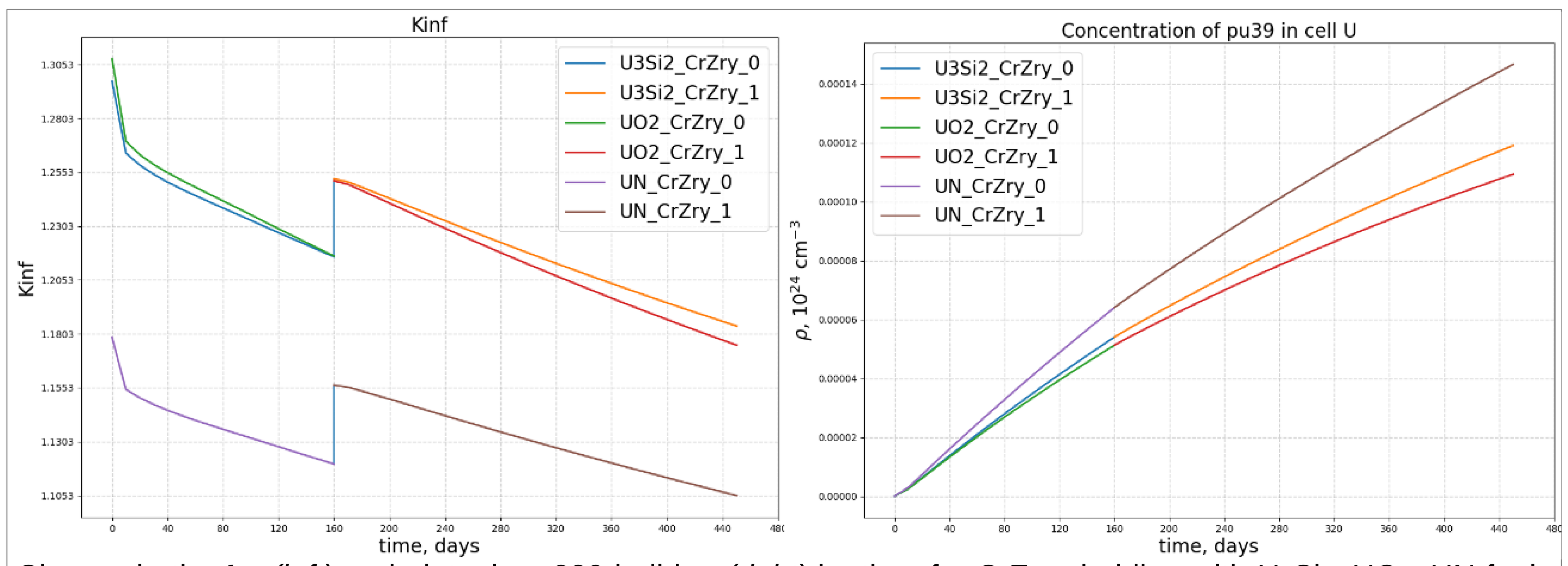
The figure shows the Infinite multiplication factors (k_∞) evolution under the influence of mechanical displacers during the first 160 days, followed by operation without displacers thereafter.

- k_∞ for SiC, Zry, CrZry, and FeCrAl at two thicknesses—330 µm (AS-thin) and 650 µm (AS-thick)—were evaluated using UO_2 fuel enriched to 4.6%.
- The ranking of these materials by decreasing k_∞ is explained by their respective neutron absorption cross-sections.

The figure illustrates the accumulation of plutonium-239 for selected ATF claddings.

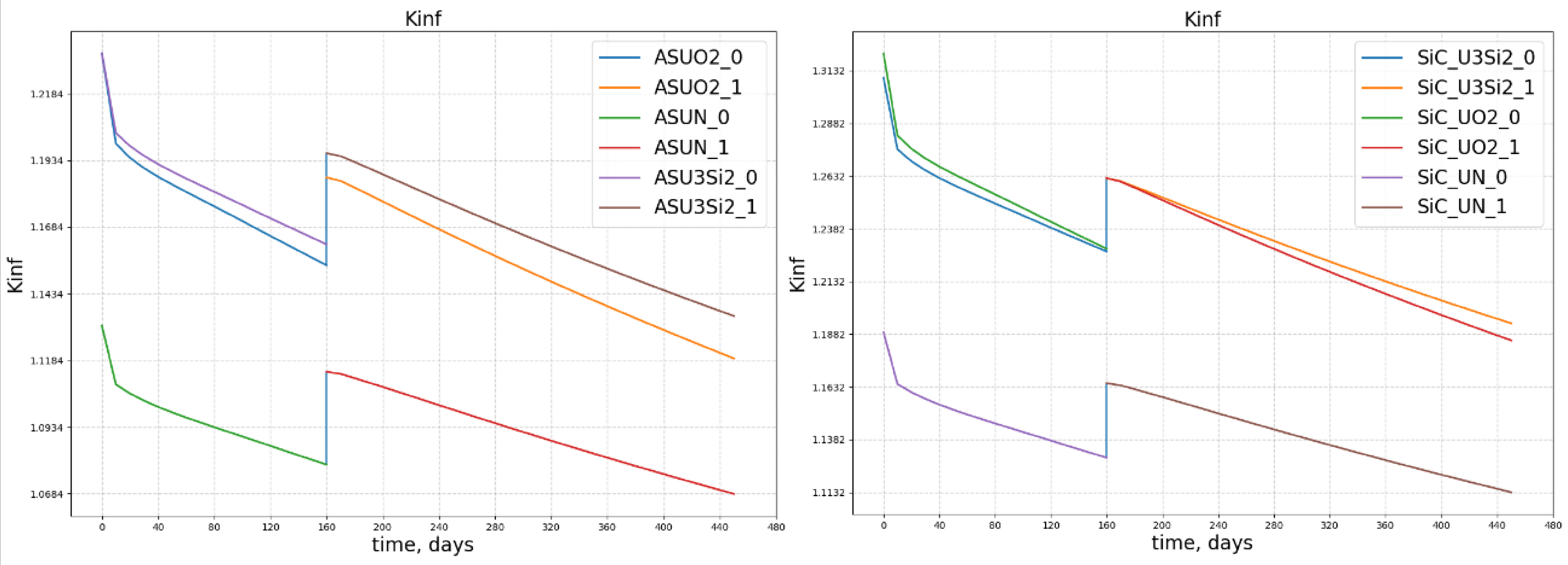
- Plutonium-239 accumulates more rapidly when displacers are used compared to when they are not.
- Claddings with higher thermal neutron absorption cross sections—such as FeCrAl—produce a harder neutron spectrum, which in turn increases resonance absorption in uranium-238 and thus leads to greater plutonium-239 buildup.





Change in the k_∞ *(left)* and plutonium-239 buildup *(right)* by time for CrZry cladding with U_3Si_2, UO_2, UN fuels are given on the figures above.

- k_∞ for U_3Si_2 decreases slowly because of the higher density of the fissile material.
- The slower decrease in k_∞ for U_3Si_2 indicates that it could achieve the necessary performance parameters within 5 wt% enrichment limit.
- The k_∞ of UN fuel is lower than that of other fuels due to several factors:
  - nitrogen exhibits higher parasitic absorption;
  - the WUR for UN—1.071 with displacers and 1.409 without—is significantly lower than the optimal value of approximately 3;
  - as fuel rod radius is not optimized for high-density fuel, leading to a pronounced neutron blocking effect.
- The spectrum shift to higher energies also increases plutonium-239 production rates in high-density fuels.

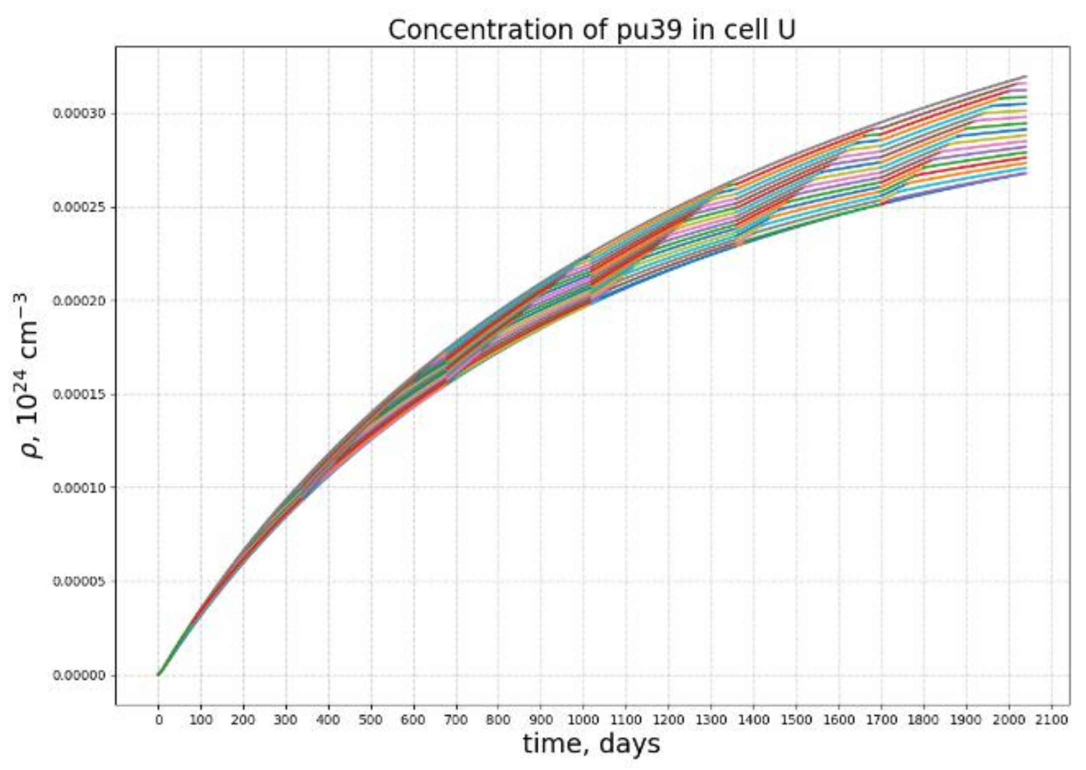


Similar trend is seen in k_∞ for FeCrAl and SiC claddings *(see figures left and right, respectively)*.

- At the end of one effective year (330 days total), modeled as 160 days with displacers followed by 170 days without, the infinite multiplication factors k_∞ for FeCrAl, CrZry, and SiC cladding with U_3Si_2 fuel (4.6% enrichment) were 1.16, 1.21, and 1.23, respectively.

Figure shows plutonium accumulation for SiC/U_3Si_2 fuel (4.6% enrichment).

- The lowest curve represents continuous operation without displacers, while the highest curve shows operation with displacers for the entire 6-year reference cycle.
- Intermediate curves correspond to different partial displacement intervals, each lasting 20 days longer than previous one, illustrating how varying the duration of displacement affects plutonium buildup.
- The graph shows that, over the 6-year cycle, burning with displacers leads to a 19% higher plutonium buildup compared to burning without displacers.



4. Conclusions

✓ Calculations show that SiC cladding is an excellent candidate for ATF. It allows using slightly less enriched uranium, especially, in combination with U_3Si_2 fuel with slow rate of decrease in k_∞ due to the higher concentration of fissile material.

✓ k_∞ of UN fuel was lower than other fuels in combination of all selected cladding candidates. It is because of parasitic absorption of nitrogen, the lower water-uranium ratio, the radius of fuel rods is not optimum for this type of high-density fuel, so the neutron block effect is high.

✓ SiC/UO_2, SiC/U_3Si_2, CrZry/U_3Si_2 and FeCrAl/U_3Si_2 fuel systems have shown good characteristics.

✓ The reference cladding thickness of 650 µm for FeCrAl exhibited a notably low k_∞. However, due to its better mechanical properties, for FeCrAl can be fabricated at half the thickness of traditional zirconium alloy claddings. In the case of FeCrAl cladding with a feasible thickness of 330 µm, the k_∞ values for all three tested fuels were noticeably lower than those with CrZry and SiC claddings, thus requiring higher enrichment to achieve the desired fuel cycle length.

✓ The multiplication factor of chromium-coated Zircaloy was slightly lower than in the case of Zircaloy/uranium fuel and requires a slight increase in the enrichment.

✓ Future work will focus on integrating multi-physics reactor level simulations with different tools to further evaluate fuel performance under dynamic operational scenarios.

5. References

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