Technical Meeting on Light Water Reactor Fuel Enrichment beyond the 5% Limit: Perspectives and Challenges

Technical Session V – Innovative Fuels

Neutronic Screening of Potential Candidate for Accident Tolerant Fuel

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This work presents a neutronic screening of potential candidates to be applied as fuel in the framework of the ATF program.

Different combinations of fuels (UO_2, U_3Si_2, UN, UO_2-BeO, UMo) and cladding materials (Zircaloy, Coated Zircaloy, FeCrAl, Stainless Steel) are evaluated using Monte Carlo code (MCNP) simulation considering a standard PWR fuel rod (single pin) reactivity analysis.

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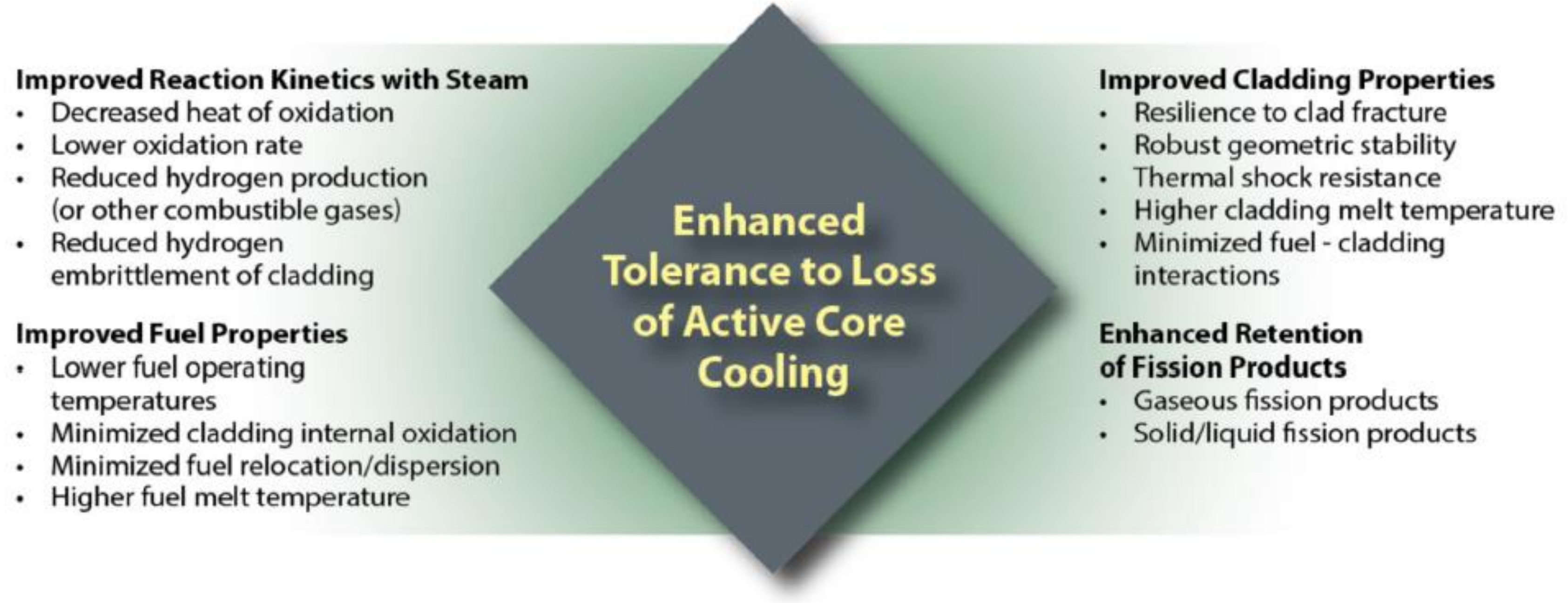
ATF – Accident Tolerant Fuel

“Fuels with **enhanced accident tolerance** are defined as fuels that can **tolerate a severe loss of active cooling** in the reactor core **for a considerably longer time period** than the current UO_2 – zirconium alloy fuel system, while maintaining or improving the fuel performance during normal operations, operational transients, and DBAs.”

ATF Attributes*



Improved Reaction Kinetics with Steam
- Decreased heat of oxidation
- Lower oxidation rate
- Reduced hydrogen production (or other combustible gases)
- Reduced hydrogen embrittlement of cladding

Improved Fuel Properties
- Lower fuel operating temperatures
- Minimized cladding internal oxidation
- Minimized fuel relocation/dispersion
- Higher fuel melt temperature

Enhanced Tolerance to Loss of Active Core Cooling

Improved Cladding Properties
- Resilience to clad fracture
- Robust geometric stability
- Thermal shock resistance
- Higher cladding melt temperature
- Minimized fuel - cladding interactions

Enhanced Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

***Metrics for the Technical Performance Evaluation of Light Water Reactor Accident-Tolerant Fuel -** *Nuclear Technology - 2016*

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According to recent NRC (Nuclear Regulatory Commission*)* document entitled: "*DRAFT PROJECT PLAN TO PREPARE THE U.S. NUCLEAR REGULATORY COMMISSION TO LICENSE AND REGULATE ACCIDENT TOLERANT FUEL**", the ATF concepts can broadly categorized as evolutionary or revolutionary.

*Draft Project Plan to Prepare the U.S. Nuclear Regulatory Commission to License and Regulate Accident Tolerant Fuel, https://www.nrc.gov/docs/ML1724/ML17248A449.pdf

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The evolutionary ATF can largely rely on existing fuel experience, material, models, and methods. Mostly are nuclear fuel designs such as coated zirconium cladding and FeCrAl alloy.

The revolutionary ATF is related to fuel which has new type of fuel, cladding material, models, and methods that has to be developed to support the licensing process, such as U_3Si_2 fuel, metallic fuel, and SiC based cladding.

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Considering ATF fuel as two main components: fuel pellet and fuel cladding, for ATF fuel pellet concepts alternative and different than standard UO_2 are being suggested and investigated around, especially fuel material that can enhance thermal conductivity (high thermal conductivity) contributing to decrease the fuel temperature, reduce fission gas release, decrease thermal and mechanical stress.

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FUEL SYSTEM : Fuel

Some of the most promising fuel material

Near-term technologies: BeO doped UO_2

Mid-term technologies: UN and/or U_3Si_2

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It is well-known that BeO presents higher thermal conductivity compared to other oxides, as well as higher melting point, reasonable low neutron thermal absorption cross section, and chemical compatibility with standard UO2 at high temperatures. Moreover, the BeO addition to the UO2 fuel pellet does not introduce significant changes in the conventional manufacturing process. The thermal conductivity enhancing due to the BeO addition can reach five times or even more compared to UO2 pellet depending on BeO concentration and fuel system temperature.

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The U_3Si_2 attractiveness is the high density (12.2 g/cm^3), considering that there are 17% more uranium atoms in a set volume of U_3Si_2 compared to UO_2 in the same volume for given a constant percentage of theoretical density.

The UN (Uranium mononitride) presents higher thermal conductivity (about factor 5) and higher density compared to standard UO_2, allowing a lower fuel central temperature, consequently decreases the energy stored per unit mass and more fuel loading for a given volume.

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The UMo (uranium-molybdenum) is a metallic fuel and it has significant higher thermal conductivity (~ ten times compared to UO_2). The density of UMo fuel is about 70% higher than that in standard UO_2, which can be very attractive in principle to increase the fuel cycle length, however molybdenum has a high neutron absorption cross section, specially ^{95}Mo isotope (about 14 barns for thermal neutron and ~100 barns for epithermal neutrons).

The molybdenum has seven stable isotopes with about 16% of abundance of ^{95}Mo, there are some studies considering the possibility of enrichment other isotopes or depletion of ^{95}Mo in order to decrease the neutronic penalty. The depletion of molybdenum in ^{95}Mo isotope can either be done by enriching the molybdenum in the light isotopes (^{92}Mo and ^{94}Mo) or in the heavy isotopes (^{98}Mo and ^{100}Mo).

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FUEL SYSTEM :Cladding

More attractive approaches for ATF fuel cladding consider the use of coatings material to improve current zirconium based alloy claddings in order to avoid major modification in the existing manufacturing process and also to become easier the licensing process. The addition of protective coatings in the existing cladding can prevent a severe oxidation and corrosion at high temperatures in the base material due to formation of a protective oxide on the surface.

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The desired characteristics and requirements for protective coating are: capability to coat in existing cladding tube (zirconium based alloys) with attractive cost, minimal design changes in reactor core, low manufacturing temperature in order to avoid any changes in the microstructure of zirconium alloy, negligible neutronic penalty, appropriate and compatible thermal properties (high melting temperature) with zirconium alloy, improved corrosion, hydrogen pickup and irradiation resistance under normal operations, enhanced resistance to high-temperature environment (steam) under accident condition.

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The coating material considered in this work are chromium and Ti_2AlC (Aluminum Titanium Carbide) in the zirconium alloy cladding (ZIRLO®).

The metallic Cr (chromium) is one of the most explored coating for zirconium alloy and have shown good performance under LOCA condition (high temperature, quenching, ballooning) and in-pile experiments are currently ongoing to evaluate the performance.

Neutronic Screening

The neutronic screening presented in this work considers the fuel rod data from the reactor AP-1000 as reference.

The selected cladding materials are: ZIRLO®, FeCrAl and AISI-348.

The select fuel materials considered are: standard UO_2, UN (Uranium mononitride), U(10%)Mo, U_3Si_2 and BeO (10% volume) doped UO_2.

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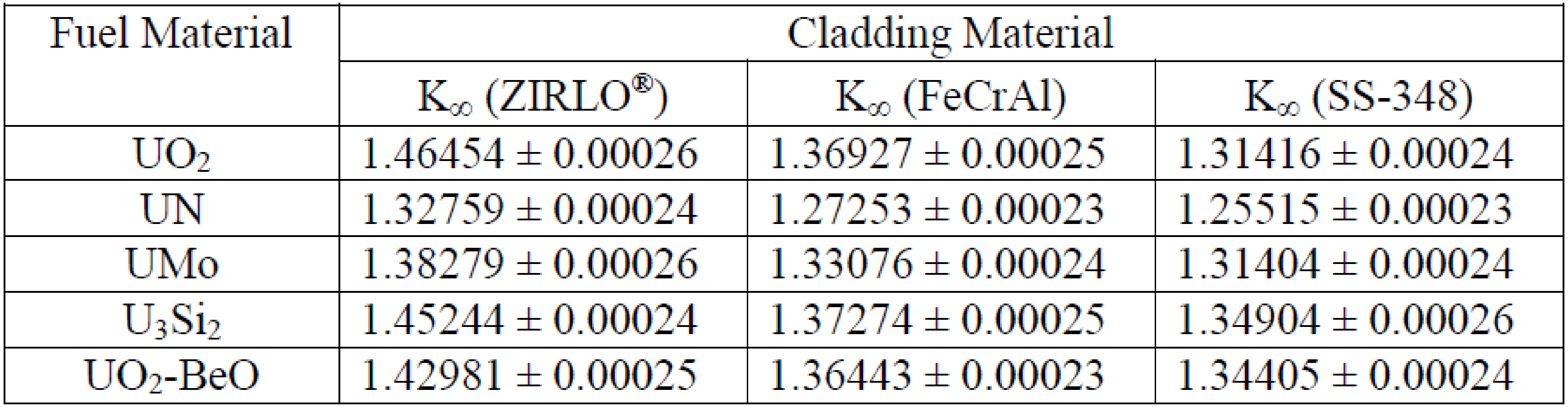
AP-1000 Data

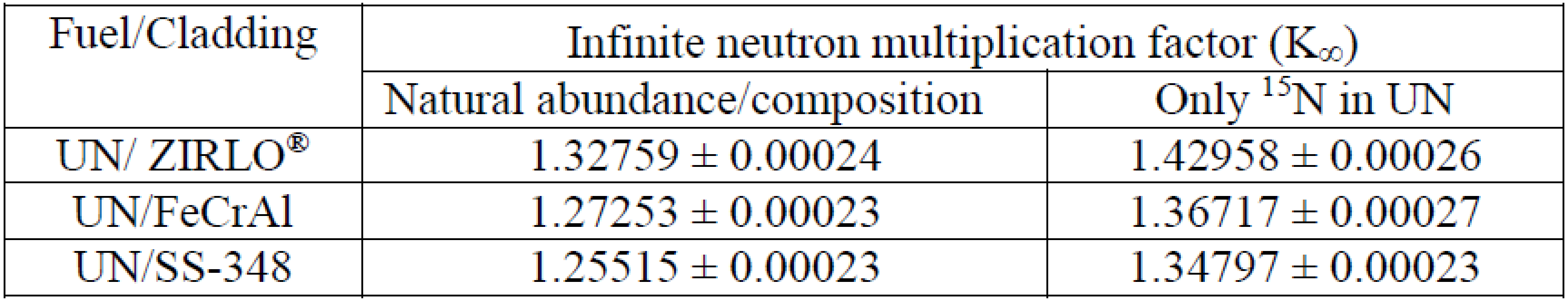
Fuel enrichment: 4.45%
Fuel pitch: 1.25984 (cm)
Fuel pellet diameter: 0.819150 (cm)
Fuel clad inner diameter: 0.83566 (cm)
Fuel clad outer diameter: 0.94996 (cm)
Cladding thickness: 0.05715 (cm)
Fuel cladding coating thickness: 40 µm and 80 µm

Obtained Results



Fuel Material	Cladding Material		
	K_∞ (ZIRLO®)	K_∞ (FeCrAl)	K_∞ (SS-348)
UO_2	1.46454 ± 0.00026	1.36927 ± 0.00025	1.31416 ± 0.00024
UN	1.32759 ± 0.00024	1.27253 ± 0.00023	1.25515 ± 0.00023
UMo	1.38279 ± 0.00026	1.33076 ± 0.00024	1.31404 ± 0.00024
U_3Si_2	1.45244 ± 0.00024	1.37274 ± 0.00025	1.34904 ± 0.00026
UO_2-BeO	1.42981 ± 0.00025	1.36443 ± 0.00023	1.34405 ± 0.00024

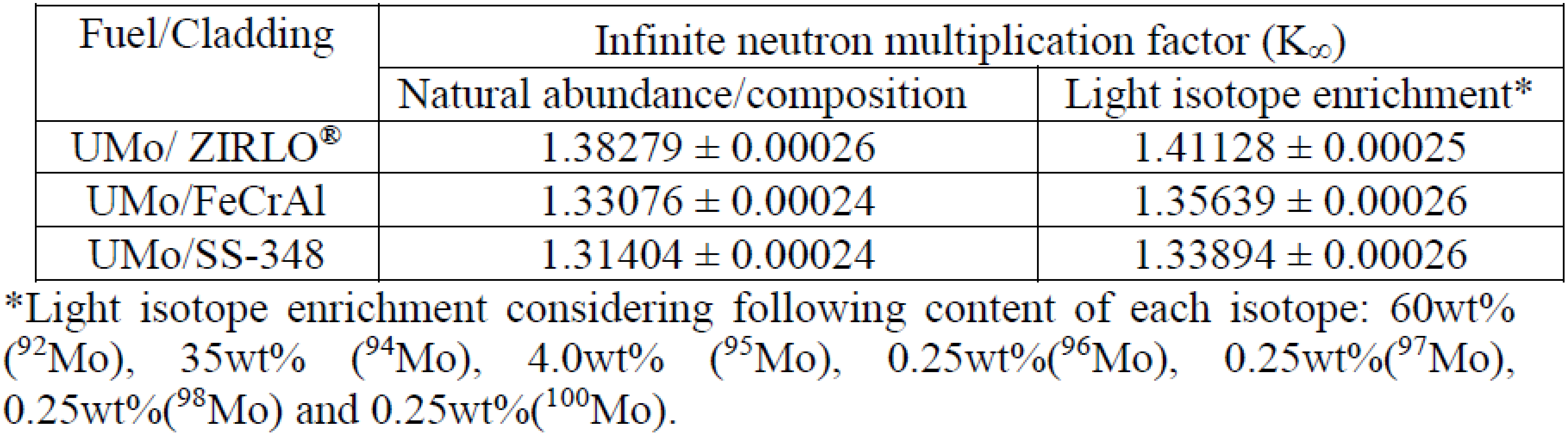
Influence of ^{15}N isotope in the UN fuel



Fuel/Cladding	Infinite neutron multiplication factor (K_∞)	
	Natural abundance/composition	Only ^{15}N in UN
UN/ ZIRLO®	1.32759 ± 0.00024	1.42958 ± 0.00026
UN/FeCrAl	1.27253 ± 0.00023	1.36717 ± 0.00027
UN/SS-348	1.25515 ± 0.00023	1.34797 ± 0.00023

Uranium nitride has ^{14}N isotope which contributes negatively for neutron economy, so to overcome this, it requires either increase of uranium enrichment level or enrichment of ^{15}N isotope level.

Influence of ^{95}Mo isotope in the UMo fuel



Fuel/Cladding	Infinite neutron multiplication factor (K_∞)	
	Natural abundance/composition	Light isotope enrichment*
UMo/ ZIRLO®	1.38279 ± 0.00026	1.41128 ± 0.00025
UMo/FeCrAl	1.33076 ± 0.00024	1.35639 ± 0.00026
UMo/SS-348	1.31404 ± 0.00024	1.33894 ± 0.00026

*Light isotope enrichment considering following content of each isotope: 60wt% (^{92}Mo), 35wt% (^{94}Mo), 4.0wt% (^{95}Mo), 0.25wt%(^{96}Mo), 0.25wt%(^{97}Mo), 0.25wt%(^{98}Mo) and 0.25wt%(^{100}Mo).

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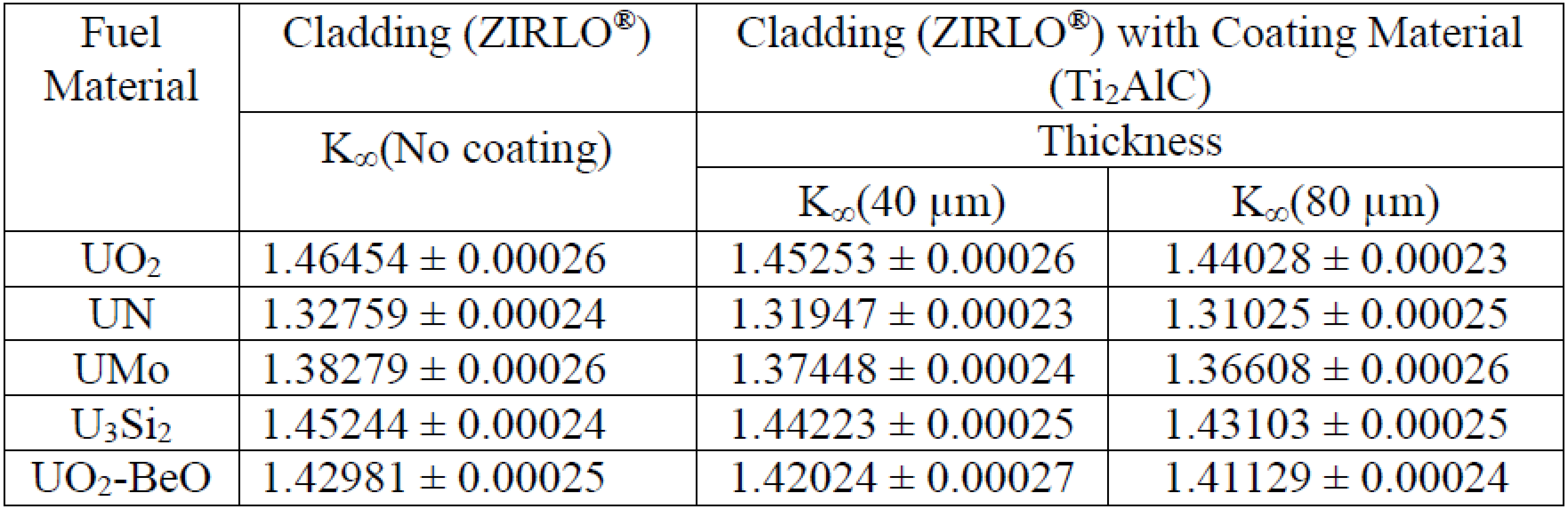
Influence of fuel cladding coating (Ti_2AlC) for different fuel material



Fuel Material	Cladding (ZIRLO®)	Cladding (ZIRLO®) with Coating Material (Ti_2AlC)	
	K_∞(No coating)	Thickness	
		K_∞(40 μm)	K_∞(80 μm)
UO_2	1.46454 ± 0.00026	1.45253 ± 0.00026	1.44028 ± 0.00023
UN	1.32759 ± 0.00024	1.31947 ± 0.00023	1.31025 ± 0.00025
UMo	1.38279 ± 0.00026	1.37448 ± 0.00024	1.36608 ± 0.00026
U_3Si_2	1.45244 ± 0.00024	1.44223 ± 0.00025	1.43103 ± 0.00025
UO_2-BeO	1.42981 ± 0.00025	1.42024 ± 0.00027	1.41129 ± 0.00024

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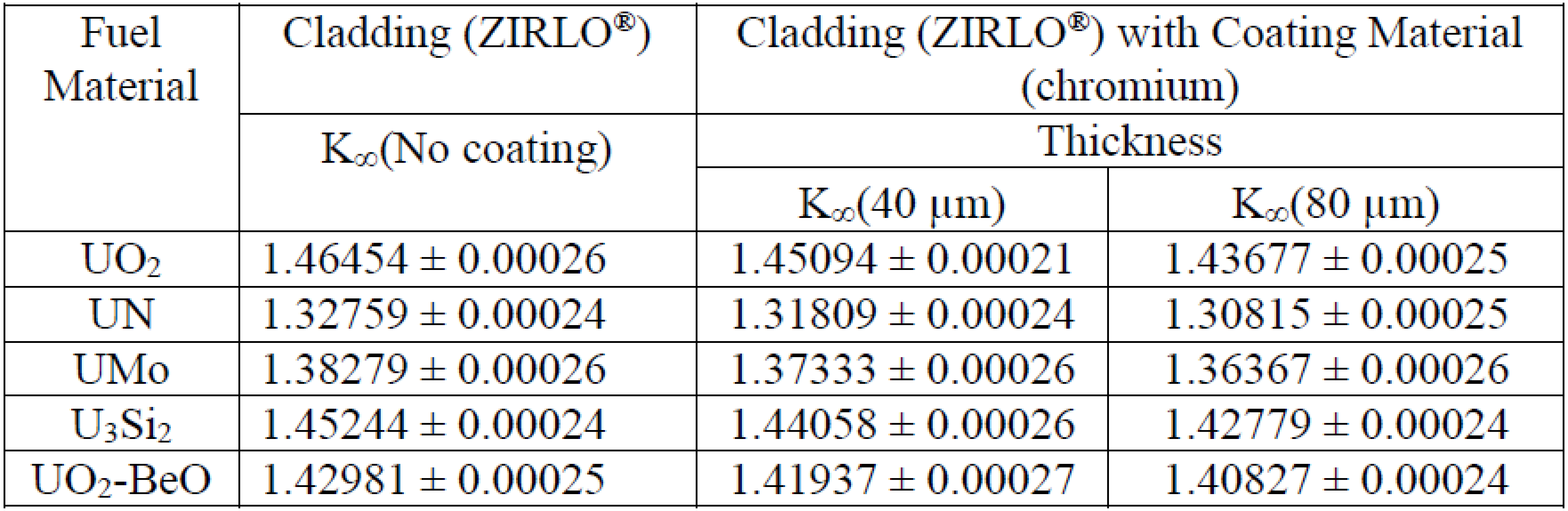
Influence of fuel cladding coating (chromium) for different fuel material



Fuel Material	Cladding (ZIRLO$^{\circledR}$)	Cladding (ZIRLO$^{\circledR}$) with Coating Material (chromium)	
	K_∞(No coating)	Thickness	
		K_∞(40 µm)	K_∞(80 µm)
UO_2	1.46454 ± 0.00026	1.45094 ± 0.00021	1.43677 ± 0.00025
UN	1.32759 ± 0.00024	1.31809 ± 0.00024	1.30815 ± 0.00025
UMo	1.38279 ± 0.00026	1.37333 ± 0.00026	1.36367 ± 0.00026
U_3Si_2	1.45244 ± 0.00024	1.44058 ± 0.00026	1.42779 ± 0.00024
UO_2-BeO	1.42981 ± 0.00025	1.41937 ± 0.00027	1.40827 ± 0.00024

Analysis and Conclusions

The overall results obtained from simulations agree with existing neutronic penalty assessment.

The cladding materials **based on iron alloys have the highest neutronic penalty**, mainly due to the presence of Fe, that is already well known as main neutron absorber.

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Three separate approaches can be considered to overcame neutronic penalty for iron alloys :

- **increase the fuel enrichment**,
- minimize the clad thickness, or
- increase the fuel mass inside the core.

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The first approach implies that the current geometry of fuel is conserved while ^{235}U enrichment is increased.

The second and third approaches are coupled in that as the clad thickness is reduced, for a given gap, the additional fuel can loaded while fixing ^{235}U enrichment at a constant value.

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The fuel system (U_3Si_2/FeCrAl) presents the best reactivity among all evaluated ATF fuel systems, but even presenting the highest reactivity it is necessary to increase enrichment level to obtain reactivity of reference fuel system (UO_2/ ZIRLO®).

The penalty associated to the presence of coating materials in the cladding could be in principle easily solved reducing the coating thickness size, as well as improving the coating properties using materials with lower neutron absorption cross section.

Thank you for your kind attention!