Egyptian Atomic Energy Authority

Proliferation Resistance of Fast Reactors and Associated Fuel Cycles
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Neutronic Performance of the (U-Pu)O_2 and (U-Pu)N Fuels in the Gas-Cooled Fast Reactor and the Impact on the Proliferation Resistance

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Introduction

- Affordable and clean Energy (Sustainable Development Goal 7) aims to ensure access to affordable, reliable, sustainable, and modern energy for all.
- Nuclear energy plays a vital role for achieving this goal. However the feasibility of nuclear energy depends mainly on the nuclear fuel cycle technology used.

- Research and development of fast reactors has growing since their inception in 1960 as promising reactors with different attractive features, including:

- Improvement of uranium utilization with closed fuel cycle.
- High breeding of fissile material.
- Reduction of radioactive waste.
- High thermodynamic efficiency and improved safety features.

Gas-Cooled Fast Reactor

- The Gas-cooled Fast Reactor (GFR) is one of the reactor concepts selected by the Generation IV International Forum (GIF) for the next generation of innovative nuclear energy systems.

- The design goal of this fast reactor is to combine various features, including high coolant temperature.

- The high coolant temperature allows for both high thermodynamic efficiency and the possibility for heat applications.

Uranium nitride fuel

- Due to its higher heavy metal (HM) density and higher thermal conductivity, uranium nitride (UN) has been proposed as an alternative to UO_2 fuel especially for fast reactors.
- One important benefit of the high density of UN fuel is the reduction of the high level waste volumes.

	UO_2	UN
Theoretical Density (g/cm^3)	10.96	14.32
HM Atom Density (g/cm^3)	9.67	13.52
Specific Heat (J/Kg K)	270 (at 200°C)	205 (at 28°C)
Melting Point (°C)	~2800	~2700
Thermal Conductivity (W/m K)	7.19 (at 200°C) 3.35 (at 1000°C)	4 (at 200°C) 20 (at 1000°C)
Linear Thermal Expansion Coefficient ($10^{-6}K^{-1}$)	10.1 (at 940°C)	9.4 (at 1000°C)
Swelling Rate (normalized to UO_2)	1.00	0.80
Fission Gas Release (normalized to UO_2)	1.00	0.45

- Replacing the oxygen with nitrogen would decrease the neutron emission in spent fuel, since oxygen has relatively high (α,n) reaction cross section.
- UN fuel has a smaller linear expansion and coefficient and swelling rate and much lower fission gas release (45% of that in UO_2 fuel).
- One superior property is that its thermal conductivity increases with increasing temperature.

Challenge of Using UN fuel

- One of the major sources of dose released from reprocessing of spent fuel is C-14 ($T_{1/2}$ =5700 years) produced due to the interactions of neutrons with N-14 or with O-17 through the reactions:

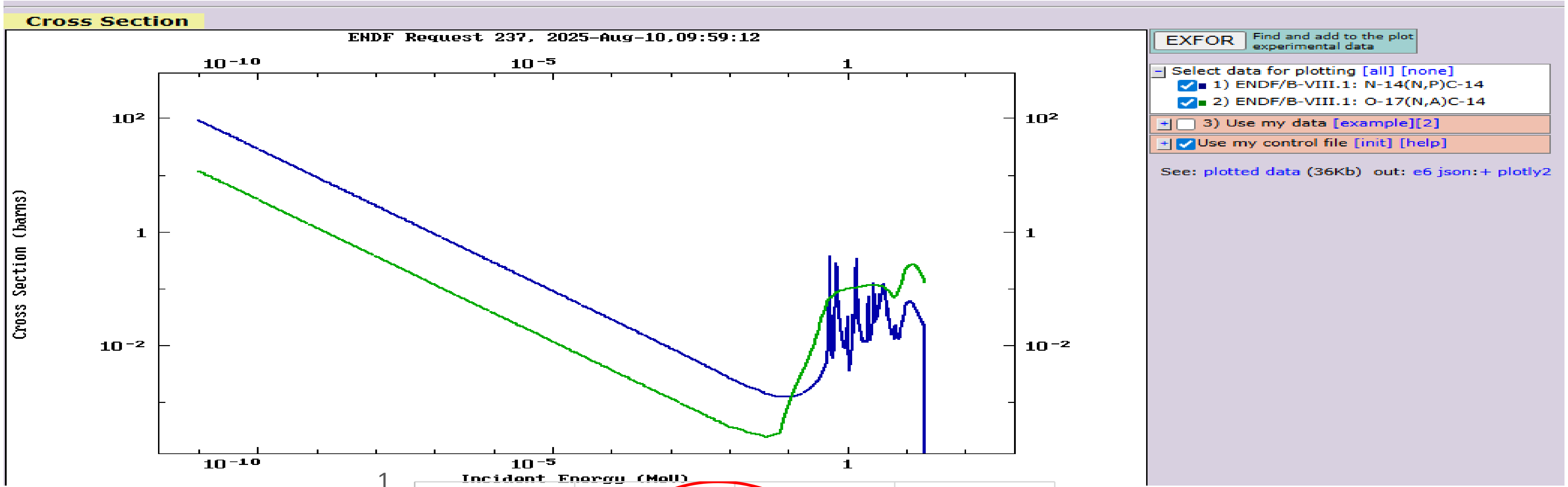
$^{14}N(n,p)^{14}C$ (UN) fuel

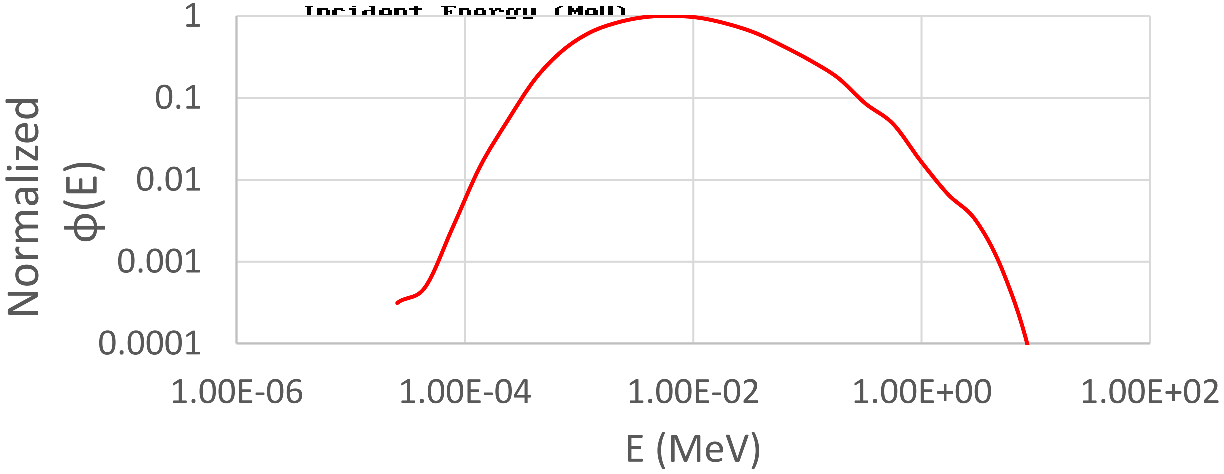
And

$^{17}O(n,\alpha)\,^{14}C$ (UO_2) fuel

- Nitrogen is found in nature with isotope abundances of 99.64% N-14 and 0.36% N-15 while oxygen has isotopic abundances of 99.76% O-16, 0.04 % O-17 and 0.2% O-18.
- Moreover, neutron cross section of **$^{14}N(n,p)^{14}C$** is higher than **$^{17}O(n,\alpha)\,^{14}C$** .
- UN fuel produces high C-14 compared to UO_2 fuel.
- UN fuel needs to be enriched in N-15 which increases the cost of the fuel fabrication.
- Direct recycling or recovering N-15 during reprocessing as byproduct can lessen this issue.

Cross sections of $^{14}N(n,p)^{14}C$ and $^{17}O(n,\alpha)^{14}C$ (from www-nds.iaea.org) and neutron flux spectrum in a typical GFR (calculated)





Simulation

- The neutronic performances of the (U-Pu)O2 and (U-Pu)N as fuels for the reactors was studied using the Monte Carlo code MCNPX2.7.0.

- The neutron cross section data for the fuel and cladding were recalled from ENDF/B-VII.0. The data of fuel was recalled at a temperature of 900 K.

- The GFR design is still under development. Different designs for the fuel have been developed . Rod geometry was selected in this study with reference power of 2400 MWth.

- The fuel assembly is built from 271 fuel rods arranged in a hexagonal mesh.

- The fuel is cladded by zircaloy-4 with a helium gap between the fuel and the clad. The fuel rod is cooled by helium gas.

- Lattice cell calculations were carried out for $(U\text{-}Pu)O_2$ and (U-Pu)N fuels such that 80 % w. of the Heave Metals (HM) is natural uranium and 20 % w. is reactor grade plutonium.

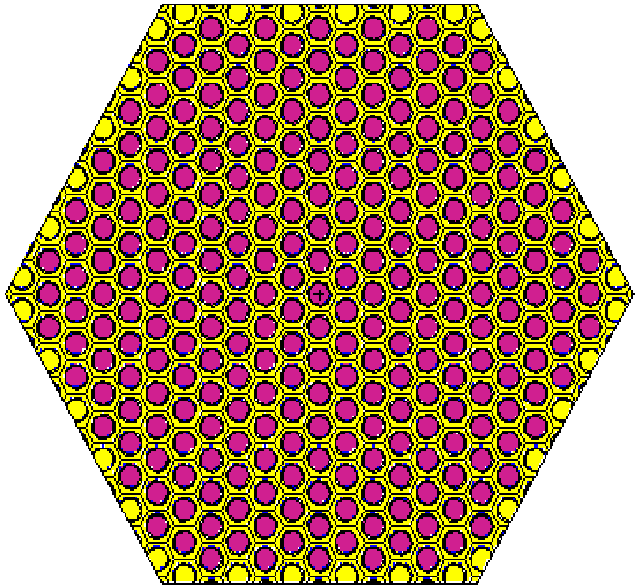
Data of GFR used in the simulation

Fuel data used in simulation.

Fuel Type	$(U\text{-}Pu)O_2$	(U-Pu)N
Nitrogen enrichment	-	99.6 %w. N-15
Density (95 % theoretical, g/cm^3)	10.55	13.585
Uranium (80 %w. of HM) isotopic Distributions (%w.)	U-238 U-235	99.28 0.72
Plutonium (20 %w. of HM) isotopic Distributions (%w.)	Pu-238 Pu-239 Pu-240 Pu-241 Pu-242	2.909 52.173 25.049 12.003 7.866

Lattice cell data used in simulation.

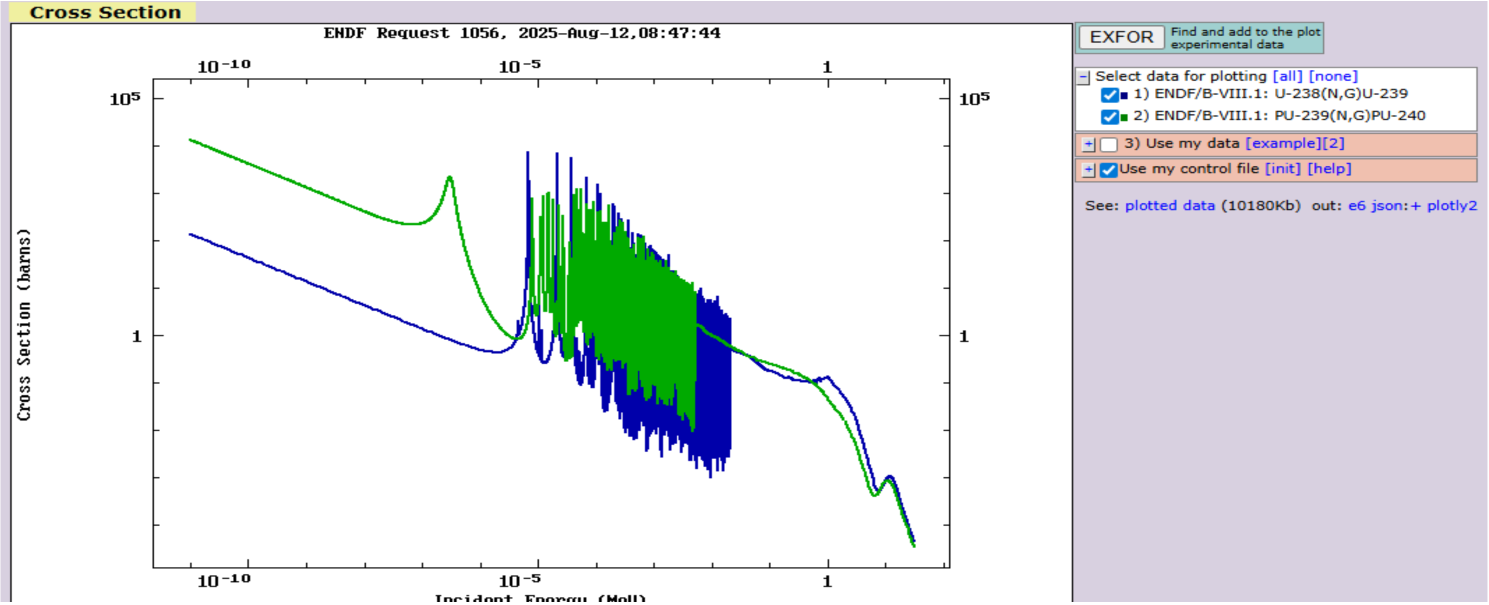
Parameter	Data
Reactor power density (W/cm^3)	100
Assembly geometry	Hexagonal
Assembly pitch (cm)	11.16
Number of rods per assembly	271
Rod cell geometry	Hexagonal
Rod cell pitch (cm)	0.64
Rod diameter (cm)	0.85
Gap thickness (cm)	0.003
Gladding material	Zircaloy-4
Gladding density (g/cm^3)	6.55
cladding thickness (cm)	0.05



MCNP model of GFR lattice cell

SBD consideration (1/2)

- Plutonium is classified depending on the distributions of its isotopes. The main two grades are weapon-grade where the concentration of Pu-240 is less than 6 or 7% and reactor-grade where it is greater than this value.
- The main issue related to the fast reactors in terms of proliferation resistance is that fast reactors generate high quality plutonium.

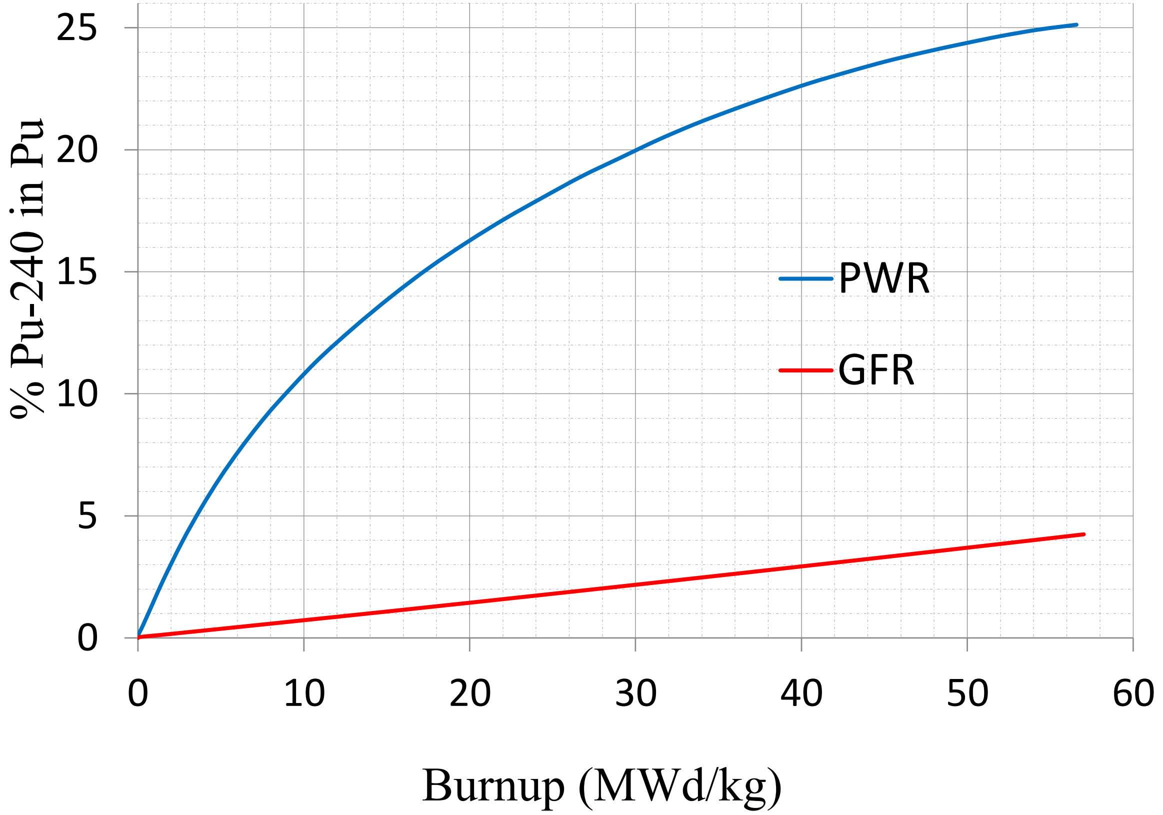


In epithermal region:

- Strong resonance absorption of U-238.
- Low cross section of $^{239}Pu(n,p)^{240}Pu$ (with respect to thermal absorption)

SBD consideration (2/2)

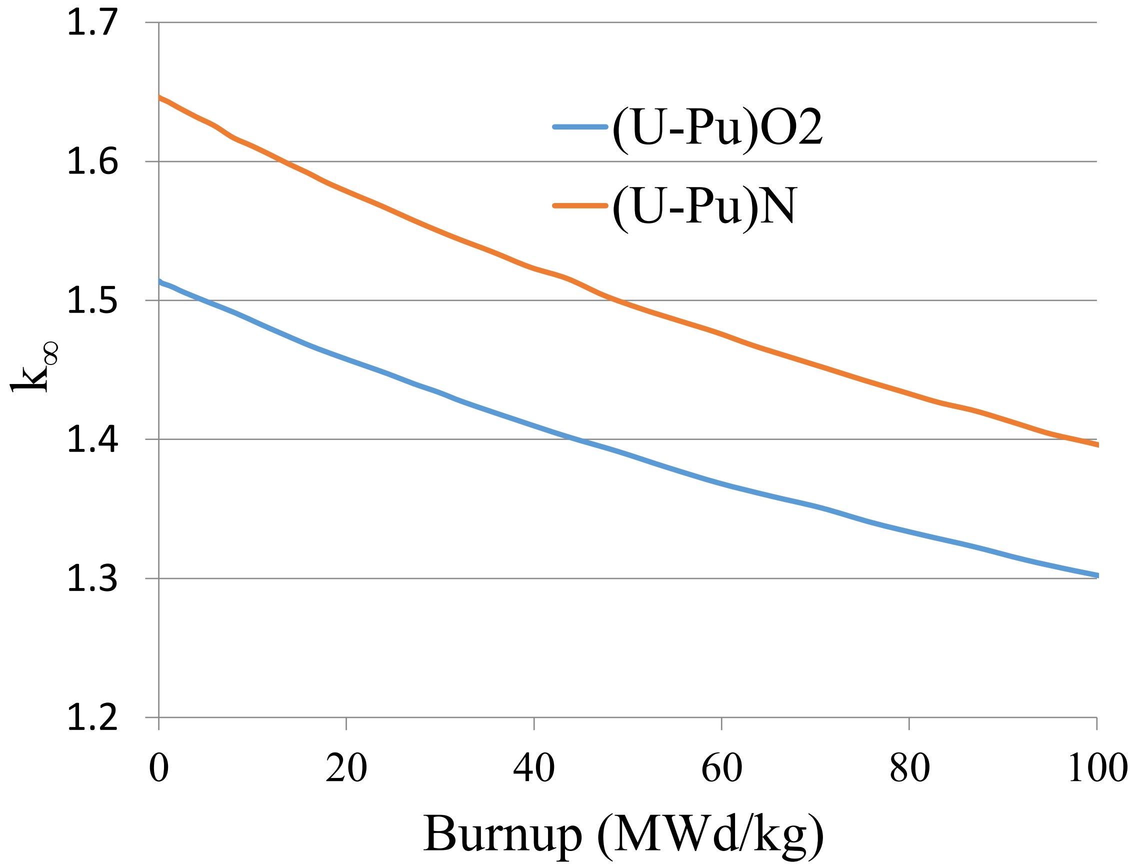
- Calculations were conducted in this study to compare between thermal and fast reactors regarding plutonium quality.
- The results showed large difference between the resulted plutonium in the two cases. After 52 MWd/kg burnup (typical today burnup of PWR) of UO_2 in PWR, the concentration of Pu-240 reaches 24.7% while in GFR is less than 4%.



- Therefore it is proposed to use plutonium generated form thermal reactors in the initial fuel design of GFR in order to complicate the proliferation.

Burnup

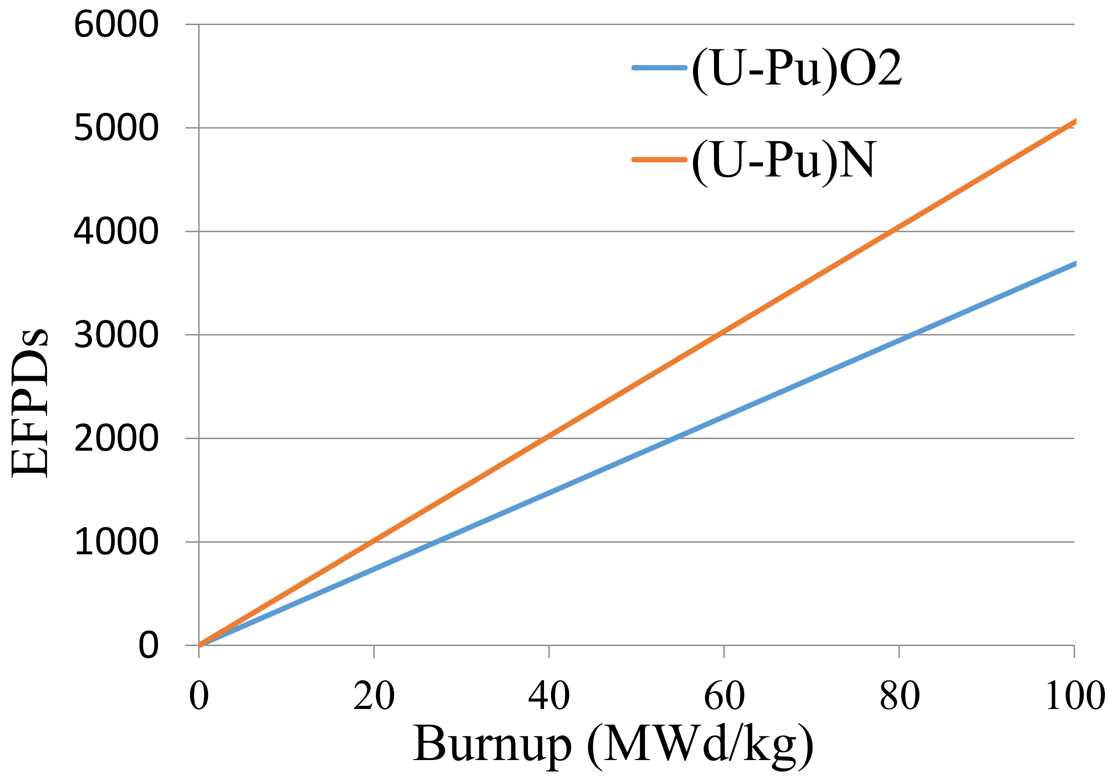
- Historically, the fuel burnups have gradually increased with time.
- The burnup license limits is determined by the fuel type and cladding material and thickness.
- there is an interest to increase the fuel burnup to 100 MWd/kg.
- Increasing fuel burnup would improve uranium utilization, reduce the high level nuclear waste and enhance the proliferation resistance.



- The conversion factor in fast reactors are high which make the fuel reactivity decreases very slowly with the irradiation time enabling very long irradiation time of the fuel.

Cycle length

- The reactor cycle is controlled by the maximum fuel burnup that the fuel can withstand (licensing limit).
- Due to the higher density of heavy metals in (U-Pu)N fuel than in (U-Pu)O_2 fuel, (U-Pu)N fuel achieves longer irradiation times than in case of (U-Pu)O_2 fuel.
- Burnup of 100 MWd/kg achieves 3670 EFPDs for the (U-Pu)O_2 fuel and 5010 EFPDs for the (U-Pu)N.



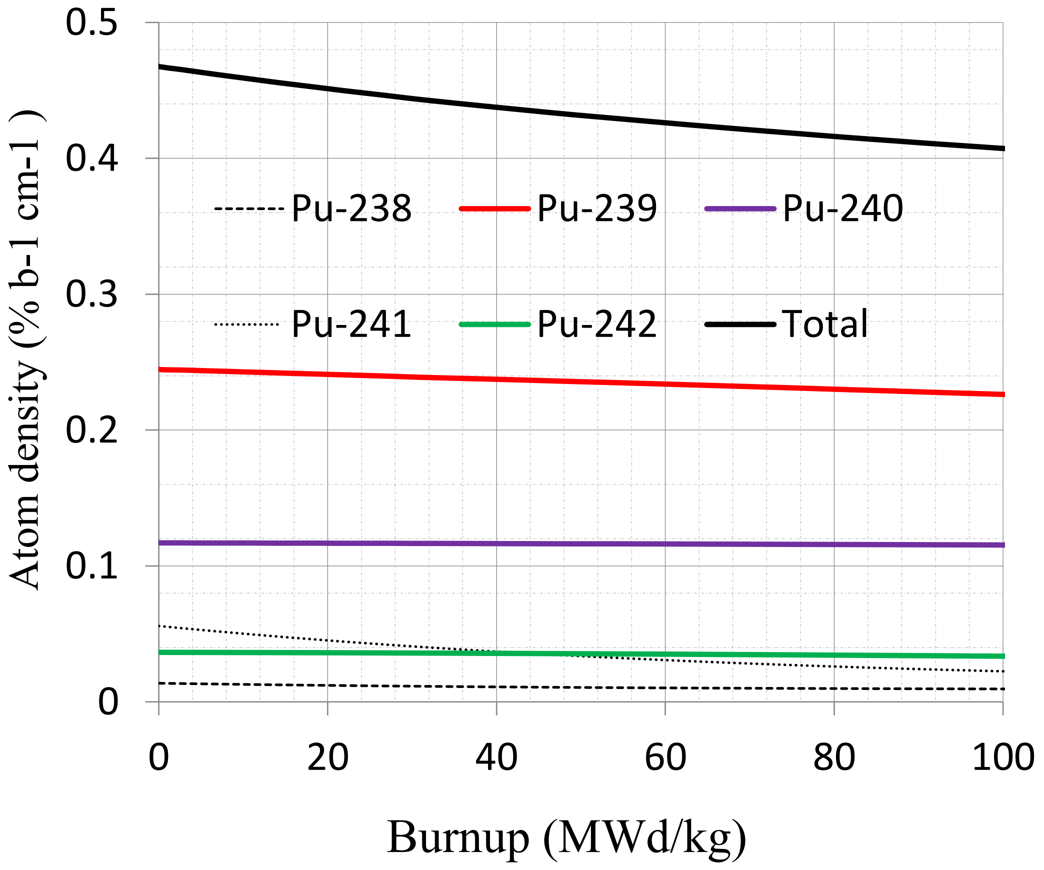
- In both cases, after burnup of 100 MWd/kg, the fuel still has high reactivity that can be recycled directly after dry processing.

Recycling

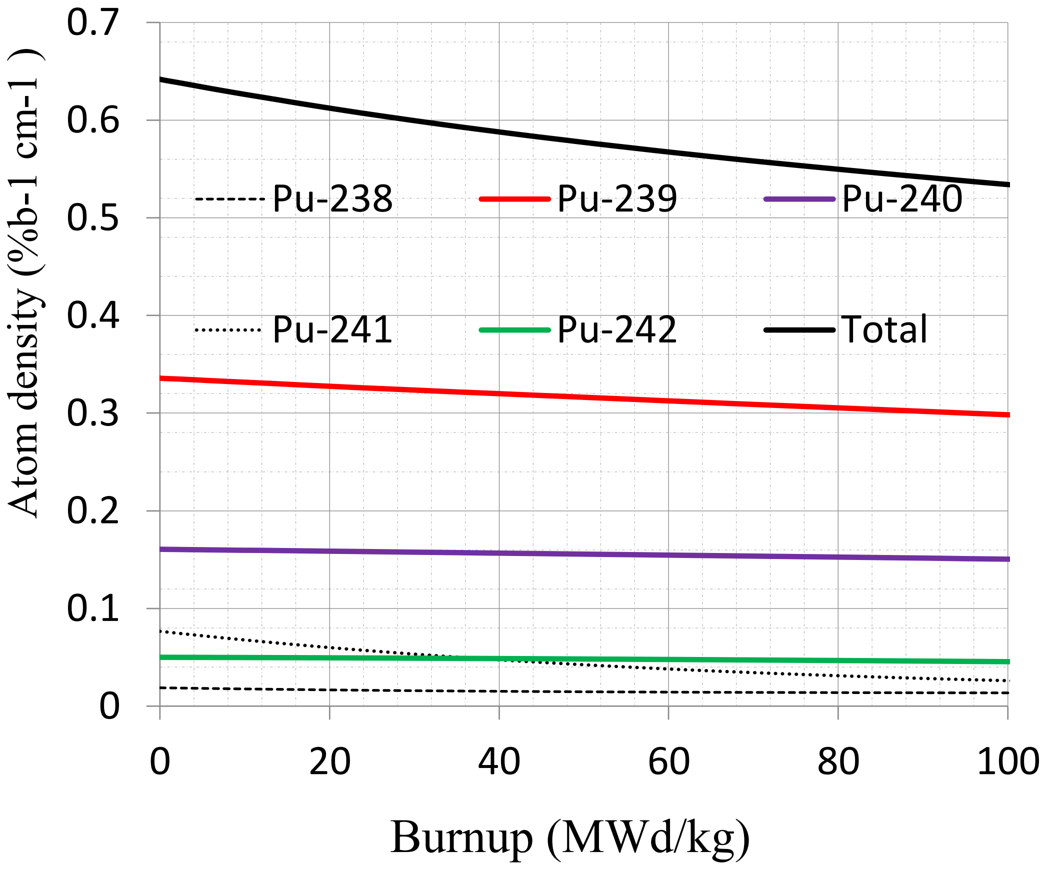
- Chemical processing of spent fuel against the proliferation resistance.
- Dry processing of spent fuel may offer a potential solution for recycling the spent fuel.
- In GFR, the fuel would be discharged at the end of core cycle after 60 or 100 MWd/kg (depending on the licensing limit) with high reactivity.
- Recycling of the irradiated fuel can be performed while the fuel management strategy can be include fresh and recycled fuel such as multi-batch core loading strategy.

Variations of the atomic densities of Pu isotopes with the burnup

$(U\text{-}Pu)O_2$ fuel

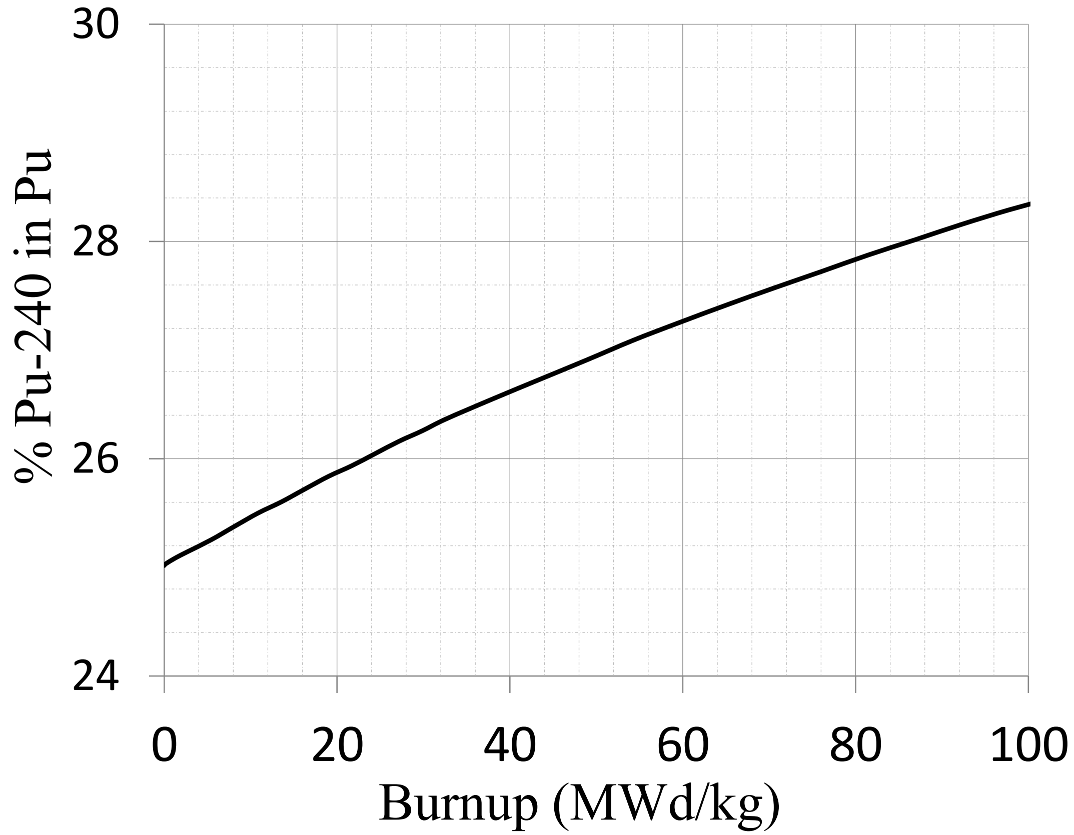


(U-Pu)N fuel



Proliferation resistance

- In fast reactors, the plutonium quality degradetes slowly with burnup.
- While at the beginning of irradiation the concentration of Pu-240 fuels is ~ 25% in the two types of fuels of interest, after burnup of 100 MWd/kg the fuels are discharged with Pu-240 concentration of ~ 28.4%.
- Therefore, it is important to initiating the fuel fabrication with reactor grade plutonium (such as that discharged from LWRs) to avoid production of weapon-grade plutonium.



- Recycling spent fuel would continually burn the generated plutonium and degradete its quality leading to the improvement of the proliferation resistance.

Generated C-14

Fuel	$(U\text{-}Pu)O_2$	(U-Pu)N
Oxygen/nitrogen composition	Natural Oxygen: O-16 99.77% O-17 0.038% O-18 0.2%	Enriched Nitrogen: N-14 0.4% N-15 99.6%
After 100 MWD/kg, **C-14 activity (mCi/kg fuel)**	1.80	8.19

Conclusions

- Fast reactors are breeders of fissile isotopes which make the fuel reactivity decreases very slowly with the irradiation time enabling very long irradiation time of the fuel.
- Due to the higher density of heavy metals in (U-Pu)N fuel than in (U-Pu)O_2 fuel, (U-Pu)N fuel achieves longer irradiation times than in case of (U-Pu)O_2 fuel.
- UN fuel produces high C-14 and it is important to use enriched nitrogen with N-15(more than 99.5%) which increases the cost of the fuel fabrication.
- Direct recycling or recovering N-15 during reprocessing as byproduct can lessen this issue.
- Fast reactors produce high quality plutonium. Therefore it is proposed to use plutonium generated form thermal reactors in the initial fuel design of GFR in order to complicate the proliferation.
- Increasing fuel burnup would improve uranium utilization, reduce the high level nuclear waste and enhance the proliferation resistance.
- Dry processing and recycling would continually burn the generated plutonium and degraded its quality leading to the improvement of the proliferation resistance.

Thank you for your attention