Id.: EN-05

NEUTRONIC EVALUATION OF A SMALL LEAD FAST REACTOR USING REPROCESSED FUELS

Paola M. Almeida[1], Jefferson Q. C. Duarte[1], Claubia Pereira[1], Clarysson A. M. Silva[1]

[1]Departamento de Engenharia Nuclear, UFMG, Departamento de Engenharia Nuclear (Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, Campus UFMG, PCA 1, Bloco 04, Anexo Engenharia, Pampulha, 31270-90 Belo Horizonte, MG, Brazil)
machadopaola813@gmail.com

Key words: ELECTRA, Lead Fast Reactor, Small Reactors.

ABSTRACT

In recent years, there has been a growing interest within the scientific community regarding the advancement of small reactor technology. Several concepts have been explored, among which the Lead Fast Reactor (LFR) gaining attention primarily due to its intrinsic safety characteristics and its capability to fission actinides, including those that may be recovered from conventional reactor used fuel. In this context, the present paper evaluates the use of reprocessed fuels in a small LFR, focusing on investigating actinide burning in a low-power fast reactor and studying its neutronic parameters during the burnup. The data of ELECTRA (European Lead Cooled Training Reactor) were used for the simulations, considering its similarities to a Small Reactor. The reactor project involves collaboration between the Royal Institute of Technology, Uppsala University, and Chalmers University of Technology in Sweden. It is a low-power fast reactor (0.5MWth), created with the purpose of demonstrating technology and conducting research. The Monte Carlo N-Particle, version 6 (MCNP6), was used in the simulations considering three scenarios for ELECTRA: the use of reprocessed fuels obtained by the PUREX, GANEX and UREX+ techniques. These fuels were simulated considering 15 years of operation under full-power conditions, during which the fuel inventory, effective multiplication factor, and neutron energy spectrum were calculated. Despite its small size and low power, ELECTRA exhibits important characteristics for actinide transmutation contributing to developing of small LFRs.

1. INTRODUCTION

In the current energy scenario, there is significant interest in developing of technologies to generate electrical energy more efficiently and safely. Small reactors have attracted attention in the research field primarily because of features such as modularization, off-site manufacturing, and their potential for integration with renewable energy sources. Among these nuclear systems, lead-cooled fast reactors (LFRs) stand out, which use lead or lead-bismuth as a coolant and operate in the fast neutron energy range. Additionally, they have the characteristic of passive safety, which is associated with the fact that lead is difficult to react with air and water, reducing the risk of explosions or fires, and its high boiling point, helping to prevent accidents that could expose the core. Furthermore, lead's high thermal capacity facilitates efficient heat exchange. Another important advantage is that lead has a relatively low scattering cross-section compared to light nuclides, which results in less moderation and favors the availability of fast neutrons to sustain the chain reaction. This is of utmost importance since the presence of fast neutrons is crucial for the fission of minor actinides present in reprocessed fuel. In this context, the present work aims to evaluate the transmutation of reprocessed fuels in a small LFR. The ELECTRA (European Lead Cooled Training Reactor) was used as a reference due to its similarity to a micro-reactor. It is a small and low-power reactor (0.5 MWth) developed by the Royal Institute of Technology, together with Uppsala University and Chalmers University of Technology in Sweden, with the aim of demonstrating the technology and conducting research [1]. The

simulations use MCNP6 to calculate the effective multiplication factor, neutron energy spectrum, and fuel evolution of ELECTRA using reprocessed fuels through three different techniques: PUREX (Plutonium and Uranium Recovery by Extraction), GANEX (Grouped Actinide Extraction), and UREX+ (Uranium Extraction).

2. METODOLOGY

The present work uses an ELECTRA model configured in MCNP6 code, which was verified in a previous study [2]. This model was configured according to the core characteristics described in the literature [3 - 6] and the results were derived from comprehensive full-core calculations, simulating 100 active cycles with 10,000 neutrons per cycle. To ensure the convergence of the fission source distribution, each simulation excluded 15 inactive cycles before initiating active tallies. The ENDF-B/VII was used in the simulations. Fig. 1 illustrates the radial view of ELECTRA model simulated by the MCNP6 code.

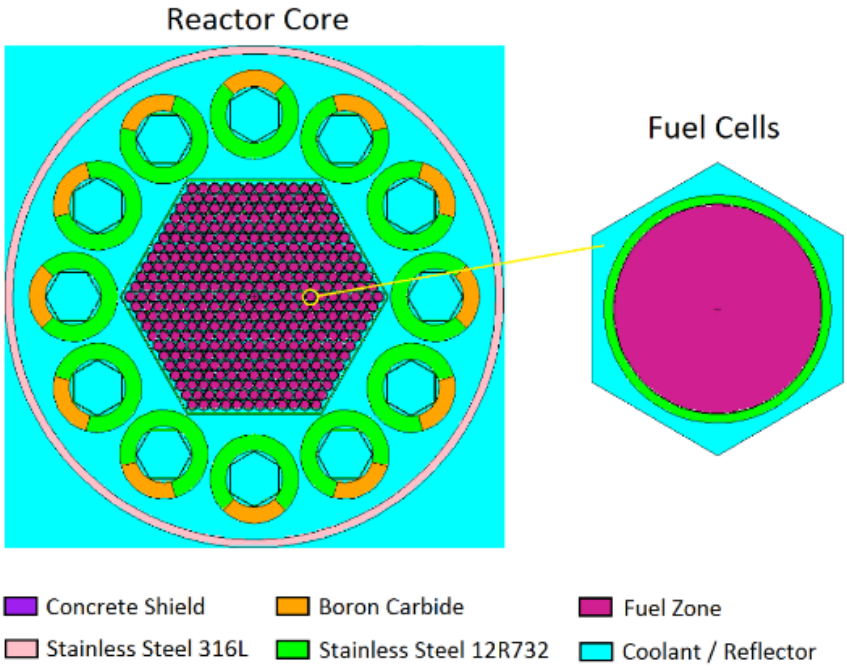


Fig. 1. Reactor core modeling illustration.

The original ELECTRA fuel employs (Pu, Zr)N, and the current study aiming to replace the Pu vector with reprocessed actinides matrix. The compositions of reprocessed fuels were derived from a spent fuel discharged from a typical Pressurized Water Reactor with initial enrichment of 3.1 % and a burnup of 33 GWd/MTU [7]. This spent fuel remained in the cooling pool for five years, and after, it was reprocessed by PUREX, GANEX, and UREX+ technique. These techniques recover Np, Pu, Am and Cm, which constitute the heavy metal matrix of the ELECTRA fuel. This paper uses the following nomenclature to describe the simulated fuels:

- FP – Fuel reprocessed by PUREX method;
- FG – Fuel reprocessed by GANEX method;
- FU – Fuel reprocessed by UREX+ method;

The Tab. 1 presents the actinide vector of the simulated fuels, and Tab. 2 depicts the recovery factor for the reprocessing method [8-10].

Tab. 1. Weight Fraction (*wf*) of Simulated Fuels

Nuclide	FP	FG	FU
^{237}Np	2.81E-02	2.85E-02	2.08E-02
^{238}Np	4.60E-05	4.68E-05	3.41E-05
^{239}Np	2.91E-03	2.95E-03	2.15E-03
^{238}Pu	1.15E-02	1.12E-02	1.14E-02
^{239}Pu	3.01E-01	2.92E-01	2.97E-01
^{240}Pu	1.03E-01	9.99E-02	1.02E-01
^{241}Pu	9.67E-02	9.39E-02	9.55E-02
^{242}Pu	3.65E-02	3.55E-02	3.61E-02
^{241}Am	-	5.00E-03	5.01E-03
^{242}Am	-	9.20E-06	9.22E-06
^{243}Am	-	6.79E-03	6.80E-03
^{242}Cm	-	1.55E-03	1.26E-03
^{244}Cm	-	1.78E-03	1.44E-03
^{245}Cm	-	6.18E-05	5.01E-05
Fissile	3.97E-01	3.86E-01	3.93E-01

Tab. 2. Recovery Factor for Reprocessing Method

Element	PUREX	GANEX	UREX+
Np	0.950	0.995	0.710
Pu	0.998	1.000	0.995
Am	-	1.000	0.980
Cm	-	0.995	0.790

The ELECTRA was designed to operate for 30 years at 50% availability, equivalent to 15 years at full power [4]. Thus, the burnup simulations consist of 15 years of reactor operation under full-power conditions at a thermal power of 0.5 MW(t), with each step representing a one-year time interval. The specific power density of ELECTRA is 6.77 W/g, which corresponds a total burnup of 37.12 GWd/ton at EOC. These simulations do not consider the actuation of reactivity control system to verify the reactivity excess during the reactor's operational lifespan.

3. RESULTS

As expected, the effective multiplication factor (k_{eff}) reduces as a function of burnup (Fig. 2) due to changes in the composition of the fuels reprocessed by PUREX (FP), UREX+ (FU) and GANEX (FG).

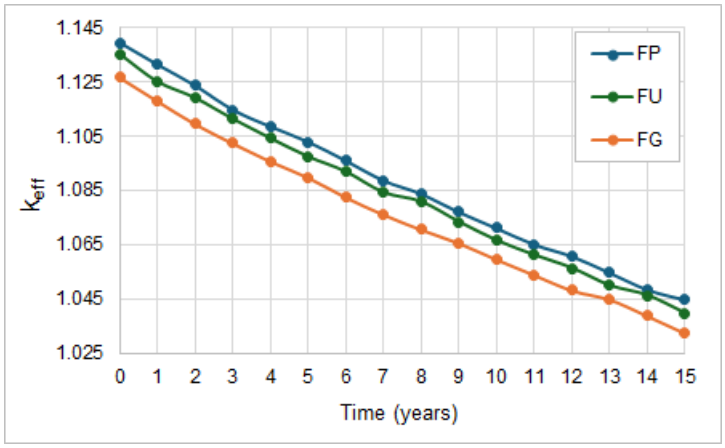


Fig. 2. Effective multiplication factor as a function of time.

All cases present a reduction of about 6% in the fissile isotopes ^{239}Pu and ^{241}Pu and an increase of 2.84% in the fission products, most of which are neutron absorbers. This behavior causes a reduction in reactivity during burnup, where the FP, FU and FG have a respective criticality decrease of 9442 pcm, 9556 pcm and 9424 pcm. However, the core reactor is supercritical for all fuels throughout the operational reactor cycle. Among the cases, the FP has the highest k_{eff}, while FG has the lowest. At the end of cycle, the FP, FU and FG has a reactivity excess of 4300

pcm, 3824 pcm, and 3138 pcm, respectively. This behavior is associated with the concentration of fissile nuclides in the fuel. The FP has the highest fissile content, while the FG the lowest (Tab. 1).

The neutron energy profile is very similar for the three fuel types. They show a hardening in the neutron energy spectrum (Fig. 3). This spectrum has a peak around 1 MeV, so the percentage of fissions is highest in the fast energy range for all cases (Tab. 3).

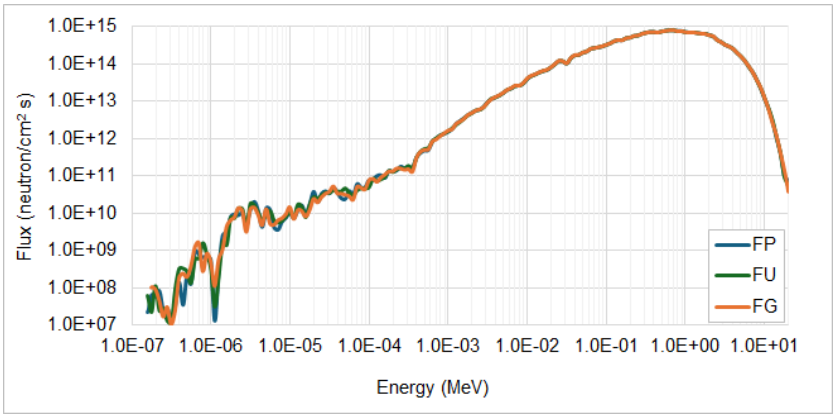


Fig. 3. Neutron energy spectrum for the evaluated fuels.

Tab. 3. The percentages of fissions caused by neutrons in three energy ranges.

Range	Energy	BOC			EOC		
		FP	FU	FG	FP	FU	FG
Thermal	< 0.625 eV	0.00	0.00	0.00	0.00	0.00	0.00
Epithermal	0.625 eV – 100 keV	14.21	14.30	14.13	13.49	13.46	13.37
Fast	> 100 keV	85.79	85.69	85.87	86.51	86.54	86.63

The Tab. 4 presents the variation in isotopic weight fraction (Δwf) for U, Np, Pu, Am, and Cm between the beginning (BOC) and end of the cycle (EOC). All fuel types present a reduction in the total quantities of Np and Pu and an increase in Am. Among them, FP has the highest reduction in Np and Pu, the highest increase in Am, and an increase in Cm, while FG and FU exhibit a decrease. Considering the hardening of the neutron spectrum (Fig. 3), this behavior may be due to the fission of ^{237}Np, ^{239}Pu and ^{241}Pu, as well as the transmutation of Pu isotopes into Am nuclides. The highest reduction of Pu may be contributing to the highest accumulation of Am and Cm.

Tab. 4. Isotopic weight fraction of heavy metal in simulated fuels.

Fuel Type		U	Np	Pu	Am	Cm
FP	BOC	0.00E+00	3.11E-02	5.48E-01	0.00E+00	0.00E+00
	EOC	1.56E-03	2.79E-02	4.83E-01	4.76E-02	4.07E-05
	Δwf	1.56E-03	-3.16E-03	-6.56E-02	4.76E-02	4.07E-05
FU	BOC	0.00E+00	2.30E-02	5.42E-01	1.18E-02	2.75E-03
	EOC	1.67E-03	2.09E-02	4.78E-01	5.84E-02	9.95E-04
	Δwf	1.67E-03	-2.10E-03	-6.36E-02	4.66E-02	-1.75E-03
FG	BOC	0.00E+00	3.15E-02	5.33E-01	1.18E-02	3.38E-03
	EOC	1.68E-03	2.84E-02	4.71E-01	5.76E-02	1.19E-03
	Δwf	1.68E-03	-3.14E-03	-6.18E-02	4.58E-02	-2.19E-03

Also, the weight fraction of uranium increases in all cases. Since there was no uranium at the BOC, it may be produced from the nuclides of another element. Uranium isotopes may be

produced by consecutive radiative captures starting from ^{234}U. All fuels exhibit an increase in the weight fraction of ^{234}U, with FU and FG showing the highest accumulation at EOC (Fig. 4). Although this nuclide is not present at the BOC, it may be produced from the alpha decay of ^{238}Pu, which is present in all fuel types.

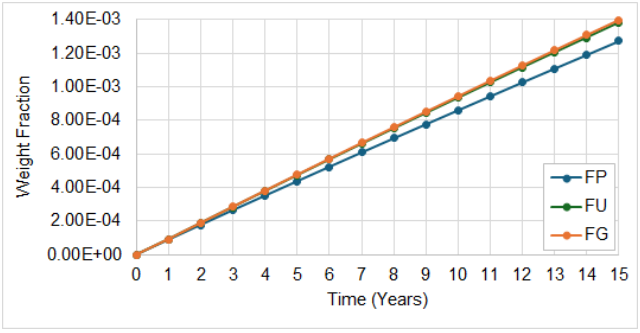


Fig. 4. Evolution of ^{234}U during the burnup.

The Fig. 5 (left) depicts the evolution of ^{238}Pu during burnup, which highlights the difference in ^{238}Pu concentration among the fuel types. In the first two years, the FG and FU present a notable increase in weight fraction of ^{238}Pu, while the FP exhibits a decrease. The presence of ^{242}Cm in FG and FP at BOC may be causing this behavior due to the alpha decay of ^{242}Cm into ^{238}Pu. The Fig. 5 (right) illustrates the evolution of ^{242}Cm during burnup, and its reduction is evident for FG and FP in the first two years. Note that at BOC, FG has the highest concentration of ^{242}Cm (Tab. 1), and thus, this fuel exhibits the greatest variation in ^{238}Pu.

After the second year, the concentration of ^{238}Pu decreases for all fuel types (Fig. 5 - left), which may be due to its fission in the fast energy range and/or its transmutation via beta decay into ^{234}U or via ^{238}Pu (n, γ) ^{239}Pu reaction.

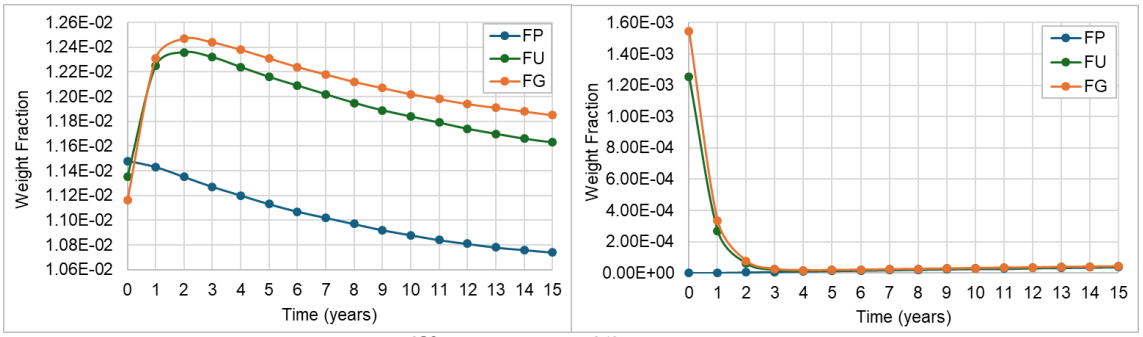


Fig. 5. Evolution of ^{238}Pu (left) and ^{242}Cm (right) during the burnup.

Among plutonium isotopes, ^{239}Pu and ^{241}Pu present the highest variation during the burnup (Fig. 6). Thus, the evolution of Pu is governed by changes in these nuclides, which decrease during the cycle for all fuel types due to fission reactions. This behavior leads to a reduction in k_{eff} during burnup. FP has the highest weight fraction of ^{239}Pu, while FG has the smallest (Fig. 6). Consequently, these fuels exhibit the highest and lowest criticality during burnup (Fig. 2). Compared to ^{239}Pu and ^{241}Pu, ^{240}Pu and ^{242}Pu exhibit small variations in their fuel evolution (Fig. 7). The Tab. 5 presents the isotopic variations of Pu nuclides, where ^{239}Pu and ^{241}Pu exhibit the highest values.

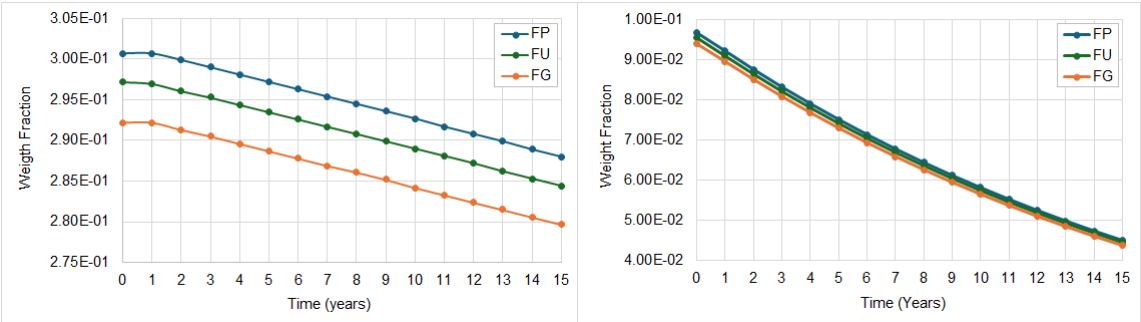


Fig. 6. Evolution of ^{239}Pu (left) and ^{241}Pu (right) during the burnup.

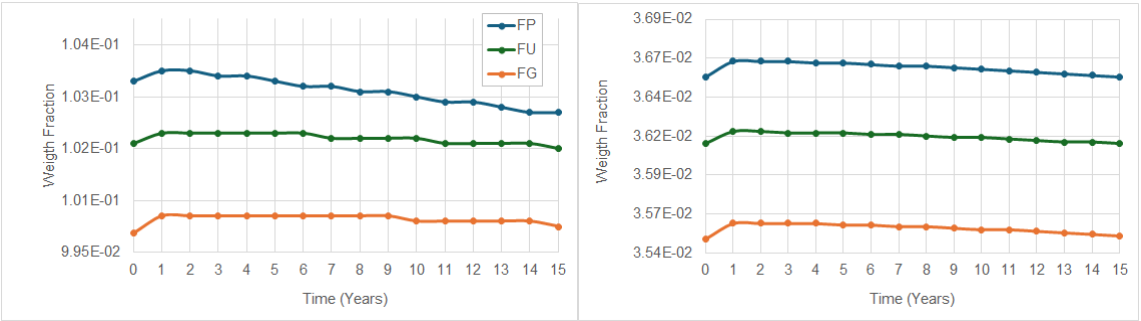


Fig. 7. Evolution of ^{240}Pu (left) and ^{242}Pu (right) during the burnup.

Tab. 5. Percentage variations in Pu isotopes.

Fuel Type	**^{238}Pu**	**^{239}Pu**	**^{240}Pu**	**^{241}Pu**	**^{242}Pu**
FP	-0.07	-1.27	-0.06	-5.16	0.00
FG	0.07	-1.25	0.01	-5.01	0.00
FU	0.03	-1.28	-0.01	-5.10	0.00

Regarding neptunium isotopes, ^{238}Np and ^{239}Np show the highest variation (Fig. 8), with the total reduction occurring within the first year of burnup due to the short half-lives of ^{238}Np and ^{239}Np (about 2 days). Through beta decay, these nuclides transmute into ^{238}Pu and ^{239}Pu, respectively. Thus, after the first year, the evolution of Np is governed by the concentration of ^{237}Np, which has a long half-life (2.14×10^6 years). Note that this concentration does not change during the burnup period (Fig. 9), and thus, the total Np variation (Tab. 4) is due to the reduction of ^{238}Np and ^{239}Np.

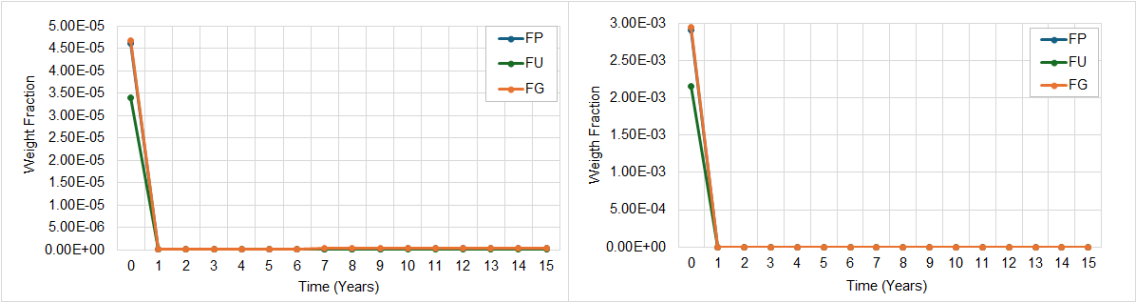


Fig. 8. Evolution of ^{238}Np (left) and ^{239}Np (right) during the burnup.

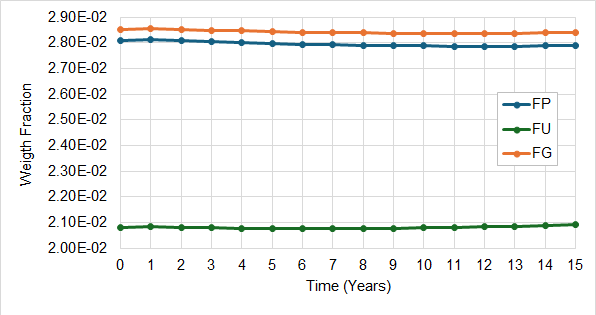


Fig. 9. Evolution of ^{237}Np during the burnup.

The Fig. 9 also shows a discrepancy in ^{237}Np concentration when comparing FU to FP and FG. This discrepancy is due to the lower recovery factor of the UREX+ method compared to the PUREX and GANEX methods.

All fuels exhibit a production of americium (Tab. 4), with ^{241}Am and ^{242}Am heaving the greatest influence on Am evolution due to their highest weight fraction. The Fig. 10 illustrates the increase in ^{241}Am and ^{242}Am during the burnup, with FU and FG exhibiting the highest concentrations due to the presence of these nuclides at BOC. The production of ^{241}Am may result from the beta decay of ^{241}Pu, while the accumulation of ^{242}Am may be attributed to the ^{241}Am (n, γ) ^{242}Am reaction. There is a significant discrepancy between the variations of ^{241}Am and ^{242}Am because the initial concentration of ^{241}Pu is higher than that of ^{242}Pu.

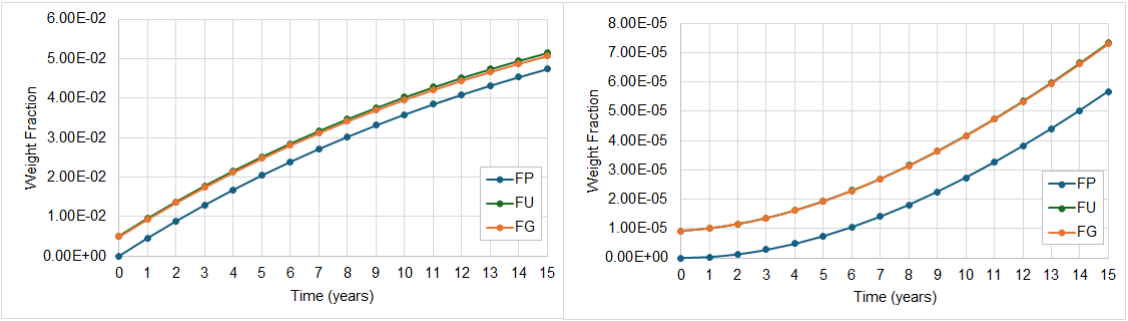
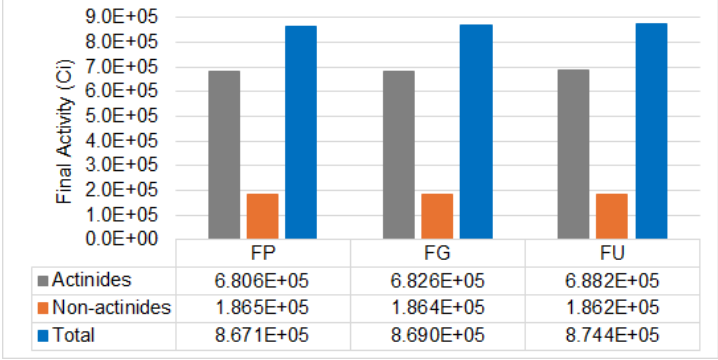


Fig. 10. Evolution of ^{241}Am (left) and ^{242}Am (right) during the burnup.

At EOC, the final activity of the fuels is similar (Fig. 11). The actinides have the greatest influence, representing about 79% of the total fuel activity. Among the fuel types, FG and FU exhibit higher activity than FP. Specifically, the total activity of FG is 1.9 kCi higher than FP, while FU's total activity is 7.3 kCi higher.



	FP	FG	FU
Actinides	6.806E+05	6.826E+05	6.882E+05
Non-actinides	1.865E+05	1.864E+05	1.862E+05
Total	8.671E+05	8.690E+05	8.744E+05

Fig. 11. Final activity of the evaluated fuels.

4. CONCLUSION

The harder neutron spectrum of ELECTRA provides the transmutation of nearly all evaluated nuclides. The simulations demonstrate that all fuels reduce Np and Pu, while those reprocessed by GANEX and UREX+ also show a reduction in Cm. However, all cases show an increase in Am during the burnup. Regarding the criticality, the presence of Am and Cm in reprocessed fuels (GANEX and UREX+) reduces the k_{eff}, but all fuels present a reactivity excess during the burnup. The evaluated features seem favorable for the use of reprocessed fuels. The evaluated parameters suggest that reprocessed fuels may be favorable for use in ELECTRA. Nevertheless, safety parameters and the action of reactivity control systems must be verified further to gain a better understanding of the use of reprocessed fuels in this reactor.

ACKNOWLEDGEMENTS

The authors are grateful to the Brazilian research funding agencies, *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq), *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES), *Fundação de Amparo à Pesquisa do Estado de Minas Gerais* (FAPEMIG) and *Comissão Nacional de Energia Nuclear* (CNEN), for the support.

REFERENCES

[1] International Atomic Energy Agency (IAEA), ELECTRA, IAEA Report, Sweden (2013).

[2] C. A. M. Silva *et al*., Neutronic Evaluation of a Small Lead-Cooled Nuclear Reactor as an Actinides Burner, *Nuclear Engineering and Design*, Vol. 417, 112796 (2024).

[3] C. Wang, A Preliminary Design Study for a Small Passive Lead-bismuth Cooled Fast Reactor, KHT Royal Institute of Technology, School of Engineering Sciences, Sweden (2019).

[4] J. Wallenius *et al*., ELECTRA: A Lead Cooled Reactor for Training and Education, *Series: Nuclear Reactor Constants*, UDC 621.039.55, Issue 4 (2015)**.**

[5] E. Suvdantsetseg, Neutronics and Transient Analysis of a Small Fast Reactor Cooled with Natural Circulation of Lead, KHT Royal Institute of Technology, Doctoral Thesis, Sweden (2014).

[6] E. Suvdantsetseg *et al*., Optimization of the reactivity control drum system of ELECTRA, *Nuclear Engineering and Design*, Vol. 252, pp. 209-214 (2012).

[7] S. Cota and C. Pereira, Neutronic Evaluation of the Non-Proliferating Reprocessed Nuclear Fuels in Pressurized Water Reactors, *Annals of Nuclear Energy*, Vol. 24, pp. 829-834 (1997).

[8] L. H. Baetslé and C. D. Raedt, Limitations of actinide recycle and fuel cycle consequences. A global analysis Part 2: Recycle of actinides in thermal reactors: impact of high burn up LWR-UO2 fuel irradiation and multiple recycle of LWR-MOX fuel on the radiotoxic inventory, *Nuclear Engineering and Design*, Vol. 168, no. 1, pp. 203–210 (1997).

[9] M. Miguirditchian *et al*., Ganex: adaptation of the Diamex-Sanex process for the group actinide separation, In: Proceedings of GLOBAL 2007 conference on advanced nuclear fuel cycles and systems, Boise, Idaho (2007).

[10] G. F. Vandegrift *et al*., Designing and demonstration of the UREX+ Process using spent nuclear fuel, Chemical Engineering Division, Analytical Laboratory, INIS-FR--2872 (2004).