BJRS
BRAZILIAN JOURNAL OF RADIATION SCIENCES

doi.org/10.15392/2319-0612.2024.2677
2024, 12(4B) | 01-19 | e2677
Submitted: 2024-08-30
Accepted: 2025-03-10

Neutronic study of ELECTRA using reprocessed fuel and depleted uranium

Silva*, C. A. M.; Almeida, P. M.; Pereira, C.

Universidade Federal de Minas Gerais, Departamento de Engenharia Nuclear, Av. Antônio Carlos, 6627, Campus UFMG, PCA 1, Bloco 04, Anexo Engenharia, Pampulha, 31270-90, Belo Horizonte, MG, Brazil.

*Correspondence: clarysson@nuclear.ufmg.br

Astract: The present work simulates the European Lead Cooled Training Reactor (ELECTRA), focusing on studying the neutronic parameters of a small fast nuclear reactor. The goal is to evaluate the possibility of incinerating minor actinides and the potential for energy production from ^{238}U. The simulations consider the following scenarios: depleted uranium mixed with the reprocessed fuel, and individual fuel rods containing only depleted uranium positioned at different locations within the reactor core. The results show that the use of reprocessed fuels could contribute to the reduction of minor actinides, while the use of depleted uranium reduces reactor criticality by acting as a neutron absorber. Most uranium nuclides do not undergo fission during burnup, which increases their isotopic concentration.

Keywords: Small Modular Reactors, Lead Cooled Reactor, ELECTRA, MCNP6

SBPR

BJRS
BRAZILIAN JOURNAL OF RADIATION SCIENCES

doi.org/10.15392/2319-0612.2024.2677
2024, 12(4B) | 01-19 | e2677
Submitted: 2024-08-30
Accepted: 2025-03-10

Estudo neutrônico do ELECTRA usando combustível reprocesado e urânio empobrecido

Resumo: O presente trabalho simula o Reator Europeu de Treinamento Resfrigerado a Chumbo (ELECTRA), com foco no estudo dos parâmetros neutrônicos para um pequeno reator nuclear rápido. O objetivo é avaliar a possibilidade de queima de actinídeos menores e o potencial de produção de energia a partir do ^{238}U. As simulações consideram os seguintes cenários: urânio empobrecido diluido ao combustível reprocesado, e varetas de combustível individuais, contendo exclusivamente urânio empobrecido, alocadas em diferentes posições no núcleo do reator. Os resultados mostram que o uso de combustíveis reprocesados pode contribuir para a redução dos actinídeos menores, enquanto o uso de urânio empobrecido reduz a criticidade do reator por atuar como absorvedor de nêutrons. A maioria dos isótopos de urânio não sofre fissão durante a queima, resultando no aumento de sua concentração isotópica.

Palavras-chave: Reatores Modulares de Pequeno Porte, Reator Refrigerado a Chumbo, ELECTRA, MCNP6

SBPR

1. INTRODUCTION

Nowadays, Small Modular Reactors (SMRs) represent a promising advancement in nuclear technology, offering potential solutions to some of the challenges associated with conventional large reactors, such as safety, cost, and deployment flexibility [1]. Among the various types of SMRs are the Lead-cooled Fast Reactors (LFRs). The neutron energy spectrum in a fast reactor offers several significant advantages compared to thermal reactors as the better fuel utilization through fissionable material use and breeding capability. Fast neutrons can efficiently fission heavy isotopes like americium, curium, and even plutonium isotopes, which are long-lived contributors to nuclear waste. This reduces the radiotoxicity and heat load of spent fuel, simplifying long-term storage and disposal. The efficient fuel utilization in fast reactors may allow certain designs to operate for decades without requiring refueling [2][3][4][5][6]. Lead-cooled can be suitable for fast reactor because its inherent safety features and high thermal efficiency. Lead has a high boiling point and does not easily vaporize, reducing the risk of large-scale releases of coolant in case of accidents. It has excellent thermal conductivity and a high heat capacity, which allows reactors to safely shut down without reliance on external cooling systems. LFRs can operate at higher temperatures compared to traditional reactors, improving the thermal efficiency of power generation systems [4][5][6][7][8]. These advantages could position Lead-Cooled SMRs as a compelling choice for future nuclear power generation, especially in overcoming some of the challenges associated with traditional reactor designs.

In this context, the present work aims to develop a neutronic study of a small-scale lead-cooled nuclear system, using data from the European Lead Cooled Training Reactor (ELECTRA) due to its similarities to a micro reactor. This paper explores the use of reprocessed fuel and depleted uranium in ELECTRA, considering both the reuse of spent

fuel and the fact that depleted uranium is a byproduct of uranium enrichment processes. The goal is to verify the possibility of incinerating minor actinides and the potential for energy generation from ^{238}U in a small fast reactor.

The simulations use the Monte Carlo N-Particle code, version 6 (MCNP6), studying two scenarios: depleted uranium diluted in reprocessed fuel and depleted uranium located in specific fuel rods within the reactor core. The first scenario evaluates different concentrations of depleted uranium diluted in the reprocessed fuel. The second examines the use of fuel rods with depleted uranium positioned at different locations in the ELECTRA core. The following sections describe the methodology employed for the simulations, present the reactor's neutronic parameters, and detail the fuel evolution throughout its operational cycle.

2. METHODOLOGY

The ELECTRA has been developed by the Royal Institute of Technology, Uppsala University, and Chalmers University of Technology in Sweden. It is a low-power fast reactor (0.5 MWth), designed to demonstrate technology and conduct research. This reactor uses the (Pu, Zr)N alloy, which has high thermal conductivity and stability enhancing reactor performance and fuel efficience. It is particularly useful in advanced reactors and high-performance nuclear fuel cycles, offering improved efficiency and reduced waste [9].

The reference fuel employs a plutonium matrix from a previous study [10]. However, the present work aimins to verify the use of reprocessed fuel and depleted uranium in ELECTRA core. Thus, the proposed fuel uses Pu, Np, Am, and Cm derived from spent fuel discharged from a typical Pressurized Water Reactor (PWR) with an initial enrichment of 3.1% and a burnup of 33 GWd/MTU [11]. This spent fuel remained in the cooling pool for five years, and after, it was reprocessed by GANEX technique [12] to obtain the reprocessed fuel. This procedure has been carried out using the ORIGEN code from

SCALE. **Table 1** presents the isotopic composition of the evaluated fuels, showing the concentration of depleted uranium.

Table 1 : Weight fraction (wf) of the simulated fuels

ISOTOPE	FUEL TYPE		
	REFERENCE	REPROCESSED	DEPLETED URANIUM
^{233}U	–	2.1080E-11	–
^{234}U	–	1.5750E-06	–
^{235}U	–	1.0339E-04	2.0005E-03
^{236}U	–	4.1896E-05	–
^{237}U	–	5.9701E-08	–
^{238}U	–	2.0647E-02	9.9800E-01
^{237}Np	–	4.8239E-02	–
^{238}Np	–	7.9031E-05	–
^{239}Np	–	4.9895E-03	–
^{238}Pu	3.4744E-02	1.8859E-02	–
^{239}Pu	5.1745E-01	4.9387E-01	–
^{240}Pu	2.3836E-01	1.6881E-01	–
^{241}Pu	1.1763E-01	1.5872E-01	–
^{242}Pu	7.9758E-02	5.9983E-02	–
^{241}Am	1.2065E-02	8.4489E-03	–
^{242}Am	–	1.5546E-05	–
^{243}Am	–	1.1472E-02	–
^{242}Cm	–	2.6180E-03	–
^{244}Cm	–	3.0001E-03	–
^{245}Cm	–	1.0442E-04	–
Fissiles	6.3508E-01	6.5269E-01	2.0005E-03

The simulations utilize an MCNP6 model developed in a previous study [13], which evaluates the neutronic parameters of ELECTRA using the reference fuel [9]. This model incorporates dimensions and composition found in the literature [10][14], with the calculated effective multiplication factor (k_{eff}) equal to 1.04094 and a standard deviation of 6 pcm [13]. The results were derived from comprehensive full-core calculations using the ENDF/B-

VII.0 cross-section library, simulating 200 active cycles with 50,000 neutrons per cycle, and excluding 50 cycles prior to initiating active tallies. The convergence of the fission source distribution was verified by the stabilization of k_{eff} as the number of active cycles increased. This methodology is a critical approach in reactor criticality calculations, ensuring accurate modeling of the fission process. The results exhibit a relative error smaller than 1%, indicating statistical stability.

Figure 1 illustrates the modeling of the reactor core using MNCP6, and Table 2 shows the geometrical dimensions of the active core of ELECTRA.

Figure 1: MCNP6 reactor core modeling.

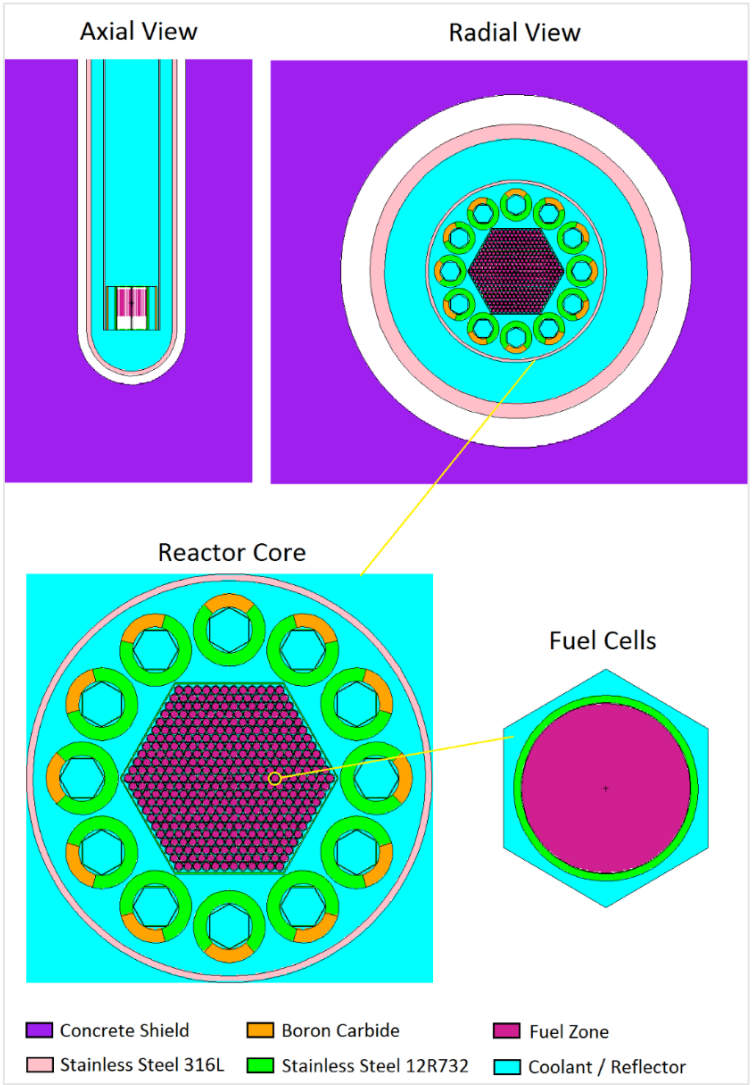


Table 2 : Main dimensions of active ELECTRA core.

DESCRIPTION	VALUE	UNIT
Hexagon flat-to-flat distance	28.2	cm
Total number of pins	397	-
Pin pitch	1.4	cm
Gap thickness	0.05	mm
Total height/Fuel height	130/30	cm
Cladding inner/outer diameter	1.16/1.26	cm
Fuel pellet diameter	1.11	cm

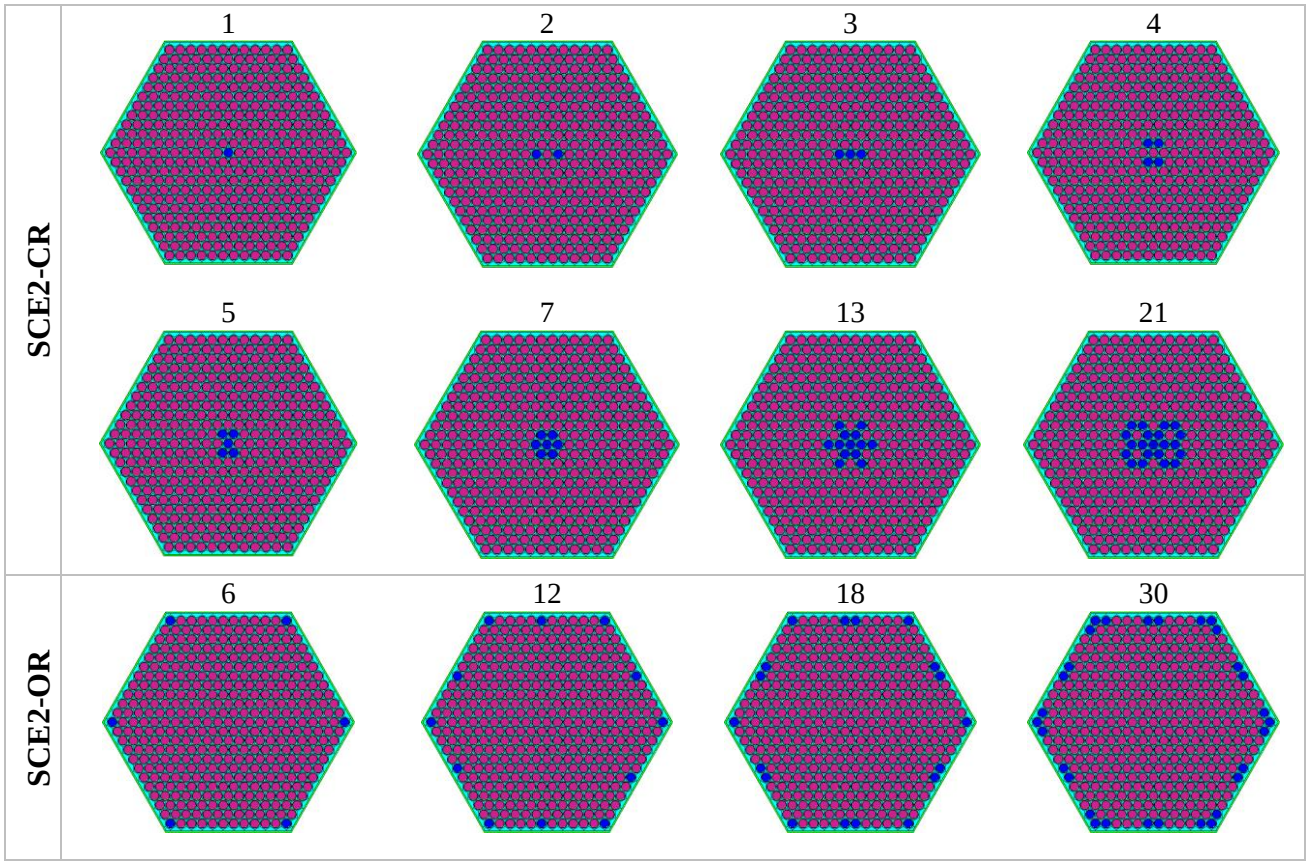
The present paper evaluates two scenarios (SCE):

- SCE1 – depleted uranium diluted in the composition of reprocessed fuel; and
- SCE2 – depleted uranium allocated in specific rods of the reactor core.

Aiming to obtain a k_{eff} closer to the reference work [9], both scenarios adjust the quantity of depleted uranium. SCE1 varies the proportion of diluted depleted uranium from 0% to 4%, and SCE2 varies the number of depleted uranium rods in the reactor core. SCE2 considers depleted uranium rods displaced into both the inner zone (SCE2-IZ) and outer zone (SCE2-OZ) of the ELECTRA core (Figure 2). In these cases, the total active length of the rods is composed of depleted uranium.

The ELECTRA was designed to operate for 30 years at 50% availability, equivalent to 15 years at full power [14]. Thus, the burnup simulations consist of 15 Effective Full Power Years (EFPY) at a thermal power of 0.5 MW(t), corresponding to a total burnup of 39.42 GWd/ton(HM). These simulations consider 15 burnup steps, where each one represents a one-year time interval or 2.63 GWd/ton(HM). This study does not consider the activation of the reactivity control system to verify the reactivity excess during the reactor's operational lifespan.

Figure 2: Number of depleted uranium rods (blue) in the ELECTRA core, in both the central region (SCE2-CR) and the outer region (SCE2-OR).



3. RESULTS AND DISCUSSIONS

Table 3 presents the k_{eff} as a function of the percentage variation of diluted depleted uranium in reprocessed fuel for SCE1. As expected, increasing the percentage of depleted uranium reduces the k_{eff} due to the higher concentration of the absorber ^{238}U in the fuel composition. Compared to the k_{eff} of the reference work (1.04094) [13], the case with 3.5% diluted depleted uranium has the closest criticality, presenting a difference of 56 pcm.

Table 3: Effective multiplication factor for diluted depleted uranium (SCE1).

%	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
k_{eff}	1.06191	1.05876	1.05751	1.05277	1.05024	1.04895	1.04494	1.04038	1.03688

Table 4 depicts the k_{eff} for different number of depleted uranium rods for SCE2 (Figure 2). As predicted, introducing depleted uranium rods results in a decrease in k_{eff}. This parameter is more affected when uranium pins are inserted into the inner zone of the core, due to the higher neutron flux in this region. Among the cases, both scenarios with 5 central pins and 18 external pins exhibit a k_{eff} closer to the reference value (1.04094) [13]. They present an absolute difference 192 pcm and 224 pcm respectively.

Table 4: Effective multiplication factor for depleted uranium rods located in the inner zone (SCE2-IZ) and outer zone of the reactor core (SCE2-OZ).

CASE	PARAMETER	VALUES							
SCE2-IZ	Number of rods	1	2	3	4	5	7	13	21
	k_{eff}	1.05302	1.05033	1.04651	1.04582	1.04286	1.03708	1.02174	1.00015
SCE2-OZ	Number of rods	6		12		18		30	
	k_{eff}	1.05487		1.04815		1.04318		1.03649	

Thus, due to the closest criticality to the reference case, the following cases will be evaluated in the next phases:

- For SCE1 – 3.5% of diluted depleted uranium (SCE1-3.5);
- For SCE2-IZ – 5 rods with depleted uranium displaced in inner zone (SCE2-IZ-5); and
- For SCE-OZ – 18 rods with depleted uranium displaced in outer zone (SCE2-OZ-18).

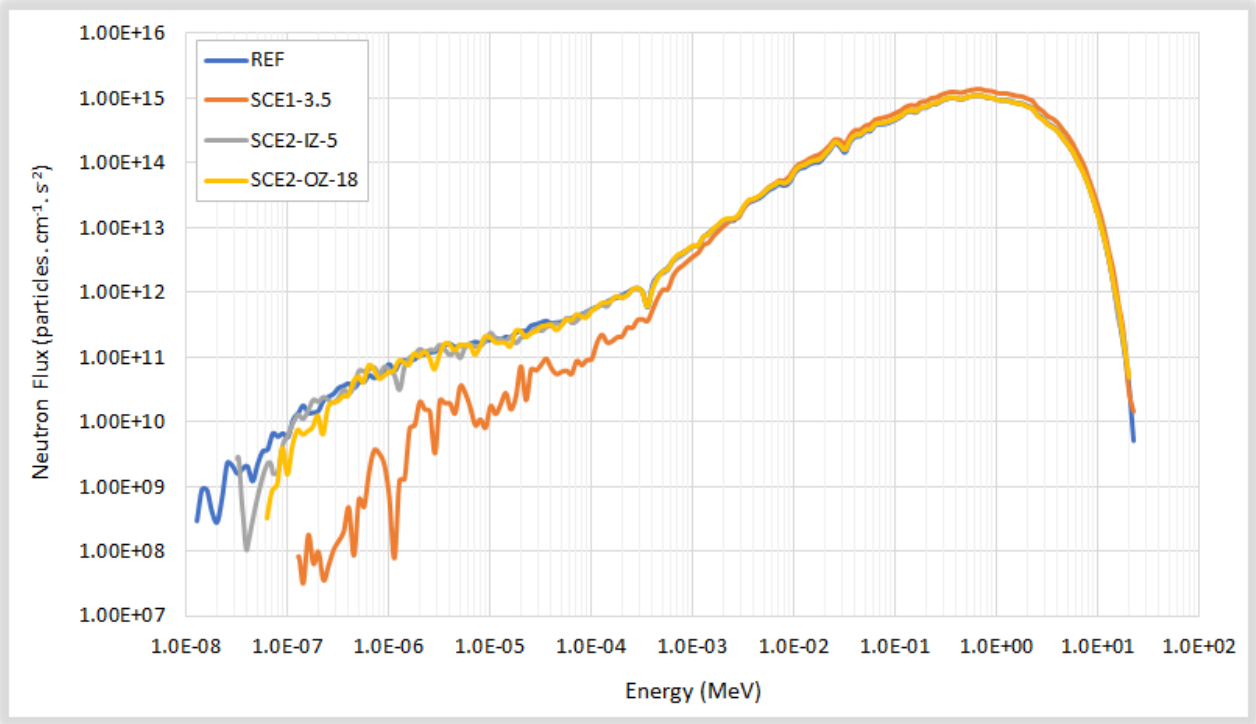
Table 5 presents the principal features of the optimized cases. Naturally, SCE2-IZ-6 and SCE2-OZ-18 each have two types of rods: fuel pins containing the reprocessed fuel, and absorber pins containing depleted uranium. On the other hand, the REF and SCE1-3.5 cases each have only one type of rod, with SCE1-3.5 featuring depleted uranium homogeneously distributed throughout all fuel pins.

Table 5: Main characteristics of the evaluated cases.

DESCRIPTION	REF	SCE1-3.5	SCE2-IZ-5	SCE2-OZ-18
Number of absorber rods	–	–	5	18
Number of fuel rods	397	397	392	379
Dilutet depleted uranium (%)	–	3.5	–	–
Fissiles isotopes at BOC (wf)	6.35E-01	6.35E-01	3.27E-01	3.27E-01

Figure 3 depicts the neutron energy spectrum for reference (REF) case and for SCE1-3.5, SCE2-IZ-5 and SCE2-OZ-18. As expected, ELECTRA present a harder neutron spectrum owing to its fast reactor characteristics. The SCE1-3.5 exhibits the hardest spectrum profile among the cases. Although they have similar k_{eff}, the dilution of uranium in the reprocessed fuel induces a hardening of the neutron spectrum, due to the distribution of ^{238}U throughout the reactor core.

Figure 3: Neutron energy spectrum fo the evaluated cases.



The radial neutron flux profile shows the most significant variation in the central region of the reactor core (Figure 4), driven by the higher neutron flux in this area. The case SCE2-IZ-5 shows a flux reduction in the central region due to the presence of six uranium absorber pins (Figure 2). SCE2-OZ-18 exhibts the highest increase of neutron flux in the inner zone of reactor core. The presence of eighteen depleted uranium pins in the outer core region (Figure 2) could be causing a redistribution of neutron flux. Absorbers in the outer core zone may lead to a compensatory increase in neutron flux in other regions of the reactor core as the system tries to balance the overall neutron flux distribution [15]. Both flux variations in the SCE2-IZ-5 and SCE2-OZ-18 cases are on the order of 4%.

Figure 4: Radial neutron flux profile for evaluated cases.

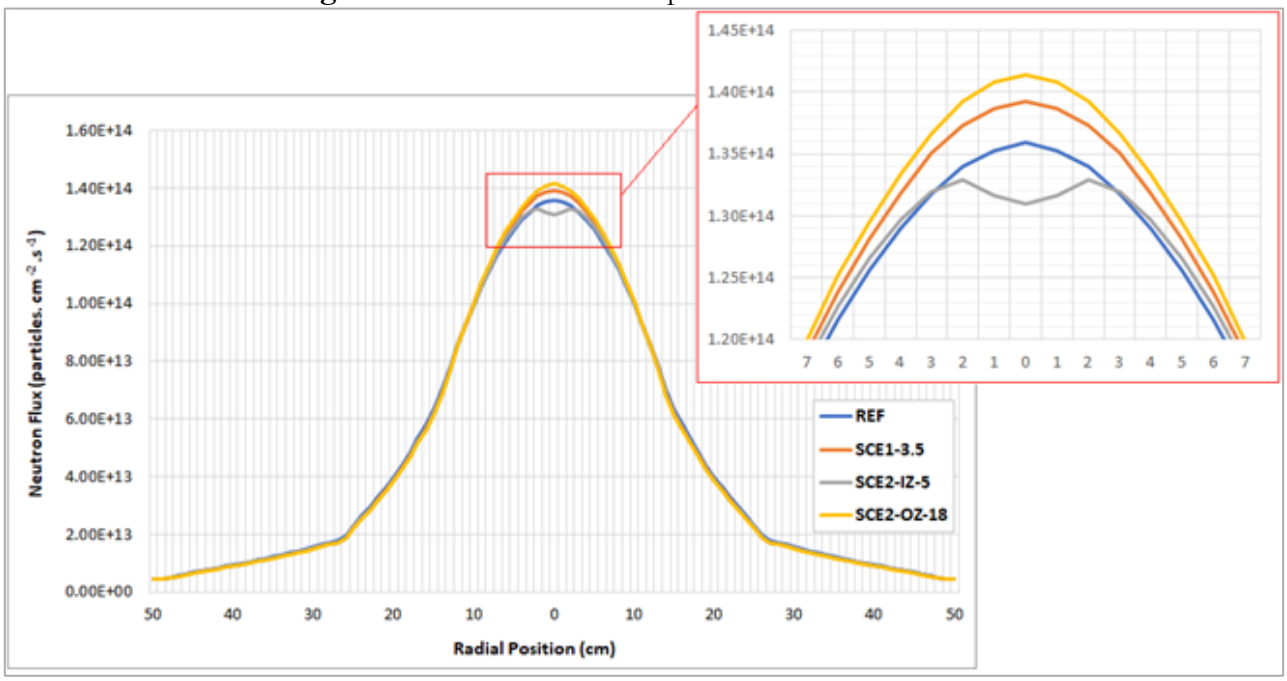


Figure 5A illustrates the criticality of ELECTRA's core for the evaluated fuels over time. At end of cycle, all cases with depleted uranium have k_{eff} smaller than reference case. SCE1-3.5, SCE2-IZ-5, and SCE2-OZ-18 have 1921 pcm, 1723 pcm, and 1271 pcm smaller than REF, respectively. This behavior could be associated with the reduction in the fission-to-capture cross-section ratio (Σ_F/Σ_C). Figure 5B shows the Σ_F/Σ_C calculated by the MCNP6 code, and it is evident that SCE1-3.5, SCE2-IZ-5, and SCE2-OZ-18 have smaller Σ_F/Σ_C

ratios than REF case. The presence of ^{238}U increases the radiative capture reactions, leading to a reduction in Σ_F/Σ_C. Furthermore, SCE2-IZ-5, and SCE2-OZ-18 have a smaller weight fraction of fissile isotopes compared to REF (Table 5).

Figure 5: (A) Effective multiplication factor and (B) fission-to-capture cross section rate as a function of fuel burnup.

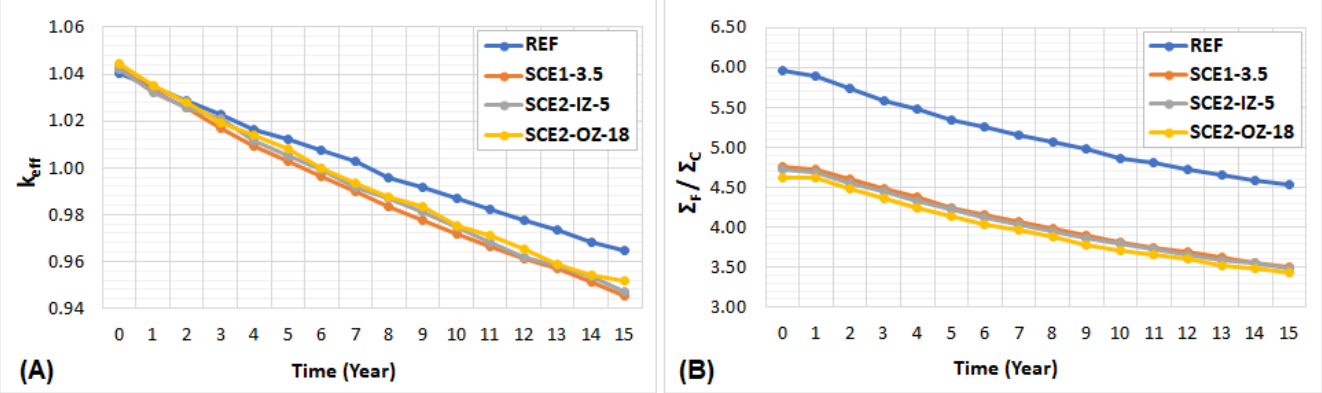


Table 6 presents the weigh fraction (wf) of principal elements at the Beginning of Cycle (BOC) and at the End of Cycle (EOC) for the evaluated cases. The weigh fraction variation (VAR) was calculated as:

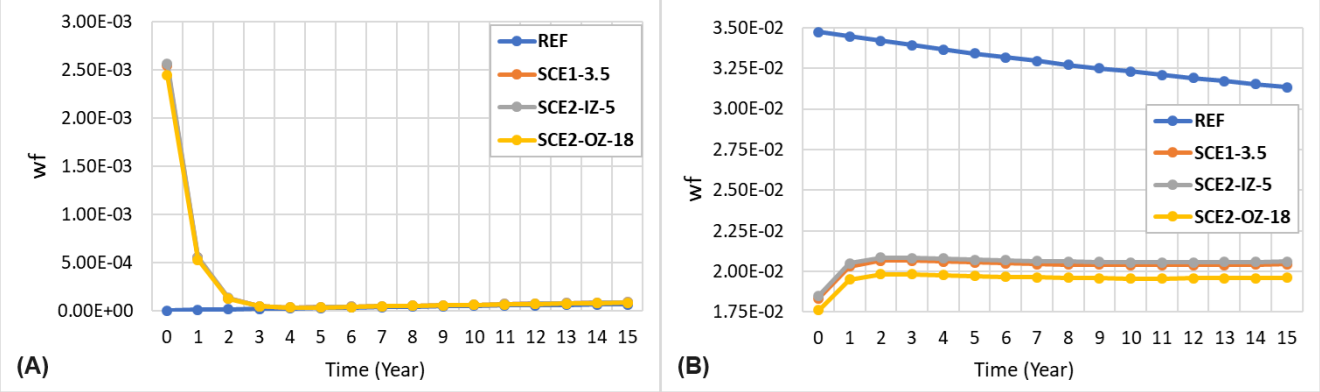
$$\text{wf (VAR)} = \text{wf (EOC)} - \text{wf (BOC)}.$$

Table 6 : Weight fraction of main elements.

CASE	PHASE	Cm	Am	Pu	Np	U
REF	BOC	0.000E+00	1.206E-02	9.879E-01	0.000E+00	0.000E+00
	EOC	7.312E-05	7.215E-02	9.278E-01	1.080E-03	4.499E-03
	VAR	7.312E-05	6.009E-02	-6.016E-02	1.080E-03	4.499E-03
SCE1-3.5	BOC	6.182E-03	2.153E-02	9.723E-01	5.758E-02	5.242E-02
	EOC	2.316E-03	1.086E-01	8.891E-01	5.357E-02	5.772E-02
	VAR	-3.866E-03	8.708E-02	-8.321E-02	-4.009E-03	5.294E-03
SCE2-IZ-5	BOC	6.181E-03	2.153E-02	9.723E-01	5.757E-02	4.301E-02
	EOC	2.312E-03	1.086E-01	8.891E-01	5.357E-02	4.784E-02
	VAR	-3.869E-03	8.709E-02	-8.322E-02	-4.001E-03	4.833E-03
SCE2-OZ-18	BOC	6.180E-03	2.153E-02	9.723E-01	5.758E-02	9.895E-02
	EOC	2.323E-03	1.086E-01	8.891E-01	5.357E-02	1.064E-01
	VAR	-3.857E-03	8.707E-02	-8.321E-02	-4.008E-03	7.421E-03

In Table 6, curium presents a reduction for the proposed fuels while exhibiting an increase for the reference fuel. Among the curium isotopes, ^{242}Cm shows the highest variation and thus drives the reduction in curium matrix. The alpha decay of ^{242}Cm to ^{238}Pu may be causing this reduction. In the first two years, the ^{242}Cm shows the highest reduction, while ^{238}Pu presents the highest increase for SCE1-3.5, SCE2-IZ-5, and SCE2-OZ-18 cases (Figure 6). Evidently, REF fuel does not have ^{242}Cm at BOC and thus presents an increase of this nuclide during burnup due to consecutive radiative capture reactions from Pu isotopes.

Figure 6: Weigth fraction of (A) ^{242}Cm and (B) ^{238}Pu during the burnup.



For the proposed fuels, ^{238}Pu begins to decrease after the first two years (Figure 7A), and this behavior could be inducing the production of ^{234}U (Figure 7B) from the alpha decay of ^{238}Pu. The nuclide ^{234}U shows the highest increase compared to other uranium isotopes. Thus, ^{234}U drives the increase in the uranium matrix for all fuel types, as shown in Table 6.

All fuels exhibit an increase in the americium matrix (Table 6). Among the americium nuclides, ^{241}Am shows the highest increase, which may be due to beta decay from ^{241}Pu. During the burnup, there is a reduction in ^{241}Pu and an increase in ^{241}Am (Figure 8). This behavior drives the increase in the americium matrix.

Figure 7: Weigth fraction of (A) ^{238}Pu and (B) ^{234}U during the burnup.

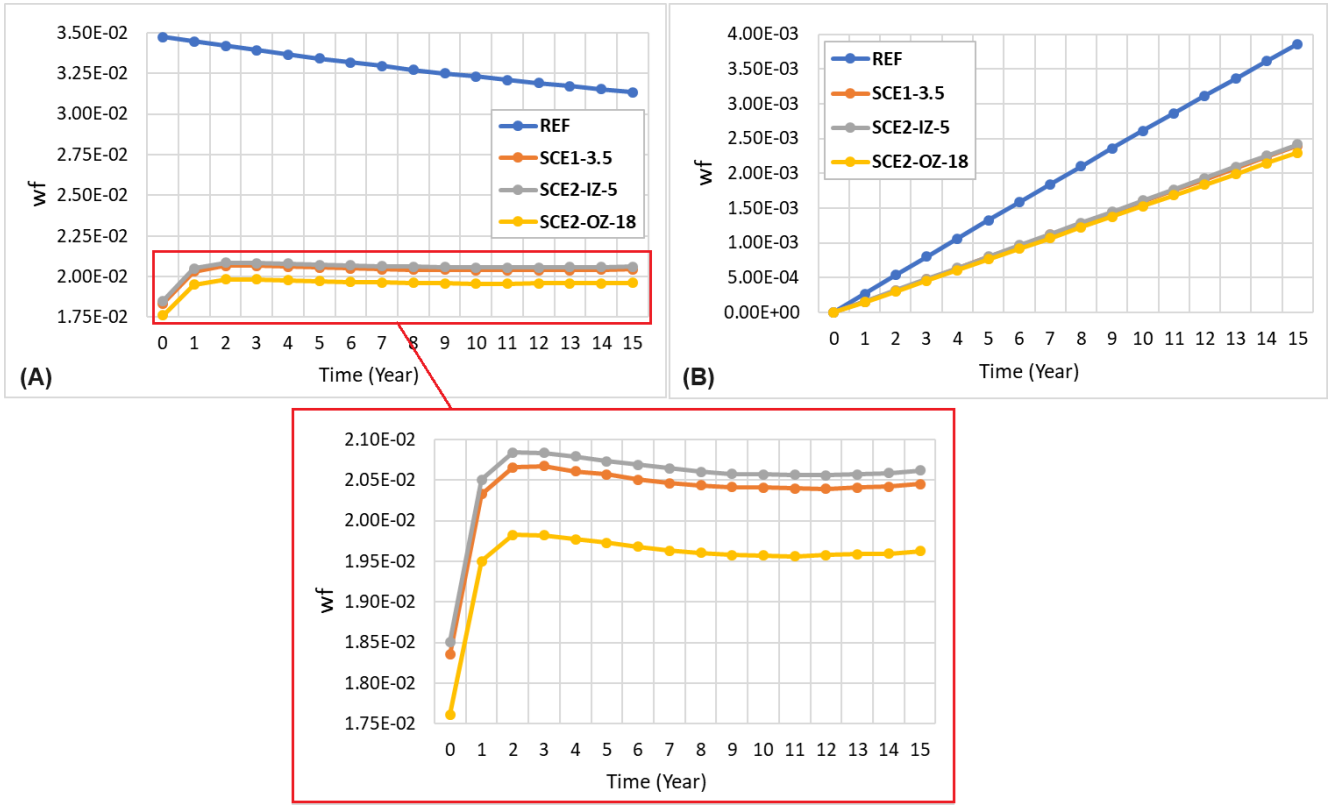
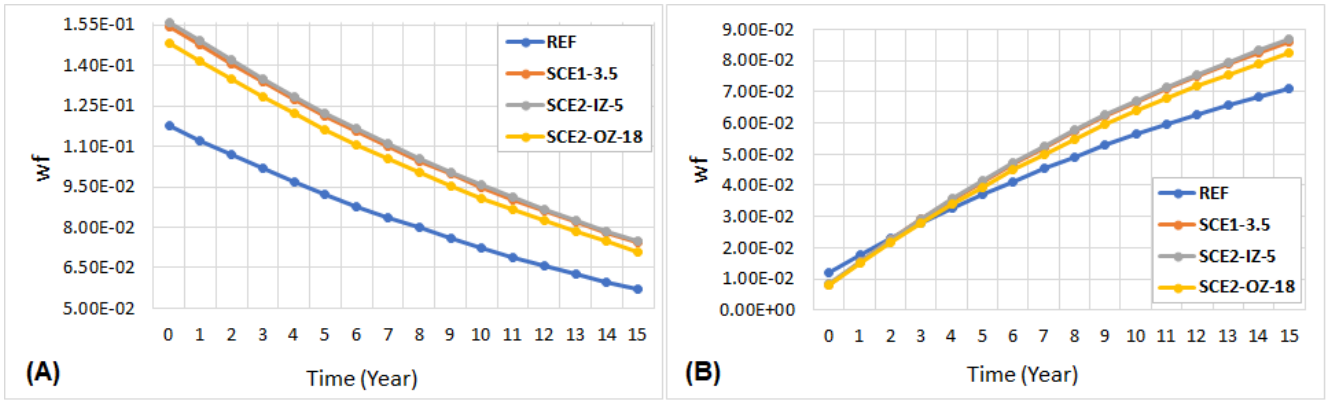


Figure 8: Weigth fraction of (A) ^{241}Pu and (B) ^{241}Am during the burnup.



For neptunium, the proposed fuels exhibit a reduction, while the reference fuel shows an increase (Table 6). The nuclide ^{239}Np causes this reduction due to the highest variation of all Np isotopes. Due to the short half-life of ^{239}Np (2.4 days), its concentration undergoes an abrupt reduction after the first year of burnup (Figure 9), and this behavior influences the reduction of the neptunium matrix.

Figure 9: Weigth fraction of ^{239}Np during the burnup.

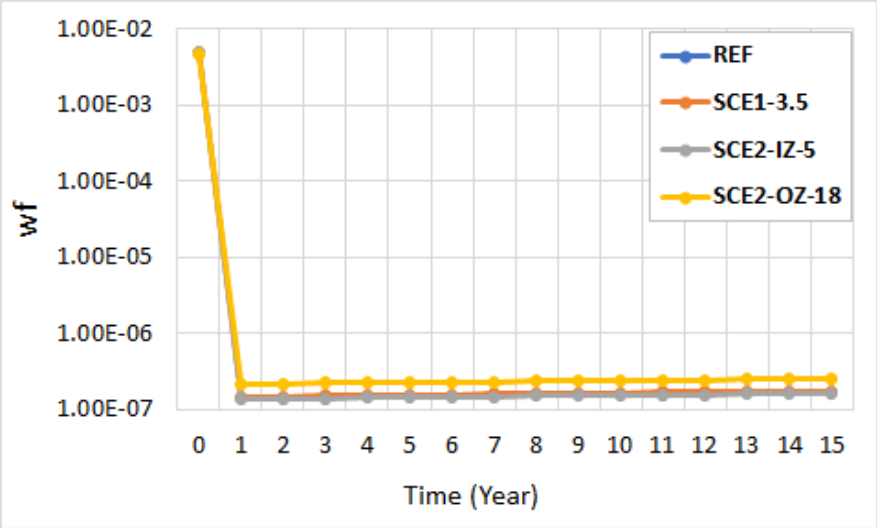
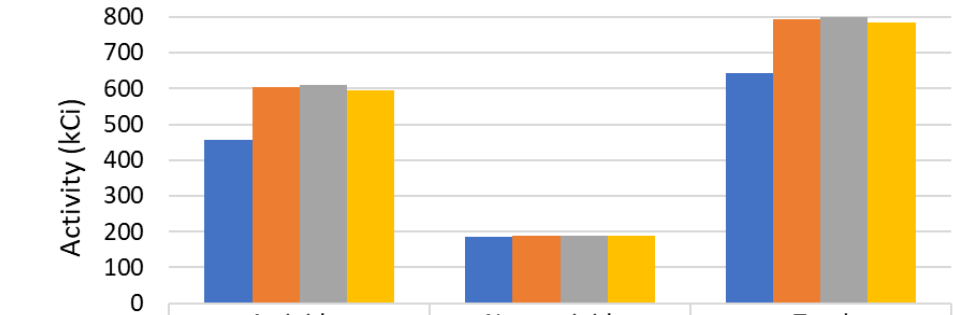


Figure 10 depicts the final activity at EOC for evaluated fuels. The total activity of the proposed fuels is higher than that of the reference fuel. For all fuels, the actinides contribute the most to the activity in the fuel, representing 76% and 71% of total activity for the proposed fuel and the reference fuel, respectively. Among the fuels, SCE2-IZ-5 exhibits the highest activity for actinides and, consequently, the highest total activity, which is 24% higher than that of the REF fuel. This behavior may be due to the greater concentration of ^{238}Pu, ^{241}Pu, and ^{241}Am in SCE2-IZ-5 at the end of the cycle, as shown in Figure 7 and Figure 8.

Figure 10: Fuel activity at end of cycle.



	Actinides	Non-actinides	Total
REF	4.575E+02	1.866E+02	6.441E+02
SCE1-3.5	6.055E+02	1.892E+02	7.947E+02
SCE2-IZ-5	6.115E+02	1.891E+02	8.006E+02
SCE2-OZ-18	5.945E+02	1.893E+02	7.838E+02

4. CONCLUSIONS

The results highlight the advantages of using reprocessed fuels, particularly due to the reduction of Np and Cm, whereas the reference case shows an increase in these elements. Additionally, the reduction of Pu is greater in the proposed fuel. However, the criticality reduction during burnup is greater due to the use of depleted uranium, resulting in a k_{eff} smaller than that of the reference fuel at the end of the cycle. Although ELECTRA has a neutron spectrum hardening, the concentration of uranium increases during burnup, indicating that most uranium nuclides do not undergo fission during reactor operation. The simulations suggest that the use of depleted uranium in ELECTRA does not present an advantage for energy production from ^{238}U, but they show that the use of reprocessed fuels could contribute to the incineration of minor actinides.

Currently, several SMR concepts based on LFRs with higher thermal power than ELECTRA are under development. The use of actinides and/or depleted uranium could potentially contribute to waste minimization, aligning with global objectives for sustainable nuclear energy. However, several technical and economic challenges must be addressed:

a) Material Challenges: Lead coolant is corrosive and requires advanced materials for cladding and structural components to withstand the harsh operating environment.

b) Fuel Fabrication Constraints: Fuels containing minor actinides present significant fabrication constraints due to their high radioactivity and complex chemical behavior, necessitating further advancements in fuel handling and manufacturing processes.

c) Reprocessing Technologies: The recycling of minor actinides and depleted uranium into usable fuel demands advanced reprocessing technologies, which are not yet fully commercialized.

d) Initial Investment: The development and deployment of LFRs with actinide incineration capabilities require substantial upfront investment in research, development, and infrastructure.

Overcoming these challenges is essential to unlocking the full potential of LFR-based SMRs for achieving sustainable nuclear energy.

ACKNOWLEDGMENT

The authors are grateful to the Brazilian research funding agencies, CNPq (Brazil), CAPES (Brazil), FAPEMIG (MG/Brazil) and CNEN (Brazil), for the support.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

REFERENCES

[1] IAEA. Technology roadmap for small modular reactor deployment. **International Atomic Energy Agency**, Vienna, Austria, 2021.

[2] SUN, X.Y., HAN, L.H., LI, X.X., HU, B. L., LUO, W., LIU, L. Transmutation of MAs and LLFPs with a lead-cooled fast reactor. **Scientific Reports**, v. 13, 1693, 2023.

[3] ADAMOV., E. Chapter 22 – New generation reactor technologies within the framework of Generation IV International Forum, Closed Nuclear Fuel Cycle with Fast Reactors. *In*: Academic Press, 2022, ISBN 9780323993081.

[4] SMITH, C. F., CINOTTI, L. **Chapter 6 – Lead-cooled Fast Reactors (LFRs), Handbook of Generation IV Nuclear Reactors**. *In*: Woodhead Publishing Series in Energy (Second Edition), Woodhead Publishing, 2023, ISBN 9780128205884.

[5] ALEMBERTI, A., TUCEK, K., M. Takahashi, OBARA, T., KONDO, M., MOISEEV, A., TOCHENY, L., SMITH, C., HWANG, I. S., WU, Y., JIN, M. Lead-Cooled Fast Reactor (LFR) System Safety Assessment. **Generation IV International Forum**, 2020.

[6] ALEMBERTI, A., FEOGHERI, M. L., HERMSMEYER, S., L. AMMIRABILE, L., SMIRNOV, V., TAKAHASHI, M., SMITH, C.F., WU, Y., HWANG, I. S. Lead-cooled Fast Reactor (LFR) Risk and Safety Assessment White Paper. **Generation IV International Forum**, 2014.

[7] JIN, X., ZHANG, Z., SUN, Y., LIU, M., XIAO, Y., GUO, H., JIANG, X., CHEN, L., GU, H. Preliminary safety comparison of lead-cooled fast reactors with advanced fuels in unprotected transients. **Nuclear Engineering and Design**, v. 411, 112419, 2023.

[8] AGBEVANU, K. T.; DEBRAH, S. K., ARTHUR, E. M., SHITSI, E. Liquid metal cooled fast reactor thermal hydraulic research development: A review. **Heliyon**, v. 9 (6), e16580, 2023.

[9] WALLENIUS, J., SUVDANTSETSEG, E., FOKAU, A. ELECTRA: European Lead-Cooled Training Reactor. **Nuclear Technology**, v. 177(3), p. 303–313, 2012.

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

[11] COTA, S.; PEREIRA, C. Neutronic Evaluation of the Non-Proliferating Reprocessed Nuclear Fuels in Pressurized Water Reactors. **Annals of Nuclear Energy**, Brazil, v. 24, p. 829-834, 1997.

[12] MIRGUIRDITCHIAN, M., CHAREYRE, L., HERES, X., HILL, C., BARON, P., MASSON, M. 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, 2007, Boise, Idaho, 2007.

[13] C. A. M. SILVA; N G. P. L. OLIVEIRA; I. K. UMEZU; C PEREIRA; A L. COSTA. Neutronic Evaluation of a Small Lead-Cooled Nuclear Reactor as an Actinides Burner. **Nuclear Engineering and Design**, Brazil, v. 417, n. 112796, 2024.

[14] WALLENIUS, J., SUVDANTSETSEG, E., BORTOT, S., PUKARI, M., JOLKKONEN, M., CLAISSE, A., OLSSON, P., EJENSTAM, J., SZAKALOS, P. ELECTRA: A Lead Cooled Reactor for Training and Education. **Series: Nuclear Reactor Constants**, Sweden, UDC 621.039.55, n. 4, 2015.

[15] DUDERSTADT, J. J., HAMILTON, L. J. **Reactor Analysis**. *In:* WILEY, J. 1st edition, 1976, ISBN 978-0471223634.

LICENSE