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Long term comparison between reprocessed nuclear fuel cycles

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ABSTRACT

Based on the idea of adopting closed fuel cycle in current pressurized water reactors (PWR) in order to reduce the use of natural uranium and recycle the spent fuel accumulated in the world inventory, this paper aims to compare two closed nuclear fuel cycles simulated at Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE). The nuclear fuel cycles compared are: i) a closed fuel cycle with recovering of plutonium (Pu) to fabricate the mixed oxide (MOX) fuel; ii) a closed fuel cycle with recovering of a transuranic matrix to fabricate the transuranic fuel spiked with depleted uranium (TRU-U)O_2. The comparison is based on the Brazilian nuclear energy system. They consider the time frame of 2019-2060 and the introduction of Angra 3 in the system. Advantages and disadvantages of using the strategy of operating with the different nuclear fuel cycles are shown, which include results regarding natural uranium consumption, spent fuel accumulation or utilization, nuclear waste and the nuclear fuel costs for both fuels.

Keywords: **comparison, fuel cycle, reprocessed nuclear fuel, MOX, transuranic.**

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1. INTRODUCTION

Nuclear power has already proven itself as one of the most reliable energy sources in terms of energy dispatch and as a low carbon energy source. However, nuclear policy continually changes due to different events and political support.

International recommendations to reduce impacts on the environment and develop a more sustainable world make it interesting to analyze ways to improve nuclear power plants or seek alternatives for their operation. Therefore, it is necessary to evaluate the economic feasibility and impacts generated by these alternatives. An alternative technology, which is already used in countries like France, The United Kingdom, Japan and Russia, is nuclear fuel reprocessing. In addition to enabling the reduction of waste, through the reprocessing and recycling of spent fuel, it is also possible to reduce the need to extract new natural resources [1].

Based on the idea of adopting a closed fuel cycle in current PWR (pressurized water reactors) in order to reduce the use of natural uranium and recycle the spent fuel accumulated in the world inventory, this paper aims to compare two closed nuclear fuel cycles. The nuclear fuel cycles compared are:

i. A closed fuel cycle with recovering of plutonium (Pu) to fabricate the mixed oxide (MOX) fuel;
ii. A closed fuel cycle with recovering of a transuranic matrix to fabricate the transuranic fuel spiked with depleted uranium $(TRU\text{-}U)O_2$.

The Brazilian nuclear energy system is used as a basis for comparison. The Brazilian energy matrix has two nuclear power plants in operation, Angra 1 and Angra 2, and a third (Angra 3) which, supposedly, should start operating in 2026 [2]. Brazil, despite mastering uranium conversion and enrichment technologies, does not have the capacity to meet the internal demands for these stages. The conversion process is carried out entirely abroad and part of the enriched uranium is also imported [3, 4]. There are also uncertainties regarding spent fuel management. Currently, spent fuel is not classified as HLW and the presidential decree “Brazilian Nuclear Policy” from 2018 states that the spent fuel will be stored at the appropriate site for future utilization of reusable material" [5]. Therefore, this context of the Brazilian nuclear energy system makes it a suitable case for the study.

The cases were modeled in the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) and the outputs and results used for the comparison between the different fuels were the consumption of natural uranium, the accumulation or use of spent fuel and depleted uranium, nuclear waste and nuclear fuel costs for both fuel cycles.

2. MATERIALS AND METHODS

The comparison of the fuel cycles is done through modeling using the MESSAGE model. MESSAGE is an energy planning model acquired by the International Atomic Energy Agency (IAEA) and modified for modeling nuclear energy systems [6]. The code represents the entire chain of an energy system, from resource extraction, conversion technologies, transport and distribution, to the end use of energy. Input data is needed on resources, conversion technologies, power plants, energy and material flows. The model allows projecting the use of resources, material and tailings flow, import dependencies, investment needs and other costs for energy supply, which makes it a convenient choice for the study carried out [6]. Mathematically, the code uses dynamic linear programming to minimize an objective function subject to constraints. The objective function comprises the sum of costs associated with generating the energy system incurred during the study period. If a new technology is introduced in recent years and its useful life exceeds the time horizon, its investment costs are reduced to fit the model. The mathematical formulation of MESSAGE including all its variables, constraints and the general form of the objective function can be seen in "MESSAGE core formulation" (2021) [7].

Among the premises for the Brazilian nuclear energy system in the period from 2019 to 2060, the extension of the useful life of Angra 1 until 2044 was considered [8]. Angra 2 operates until 2040, considering its useful life of 40 years. Angra 3 begins its construction in 2010, according to the Power Reactor Information System (PRIS) [9] and starts operating in 2026 [2]. The nuclear reactors at the three plants are PWR and the reactors from Angra 2 and Angra 3 are identical [10].

The technical data considered in this work, referring to each of the three plants, can be found in Table 1.

The fuel cycles consider the reprocessing of usual uranium oxide (UOX) from a PWR with initial enrichment of 3,1% and burnup of 33 GWd/t HM [15]. The mixed oxide (MOX) fuel is fabricated from the recycling of plutonium from the PUREX technique. The reprocessed uranium, fission products and minor actinides from reprocessing are not reintroduced in the system and are considered high-level waste (HLW). MOX fuel contains 7.23% of plutonium and 92.77% of depleted uranium. This composition is equivalent to about 4.5% enriched UOX [16]. Nuclear power plants utilize one-third of MOX and two-thirds of UOX fuel in their core.

Table 1: Technical and economic characteristics [6, 9-14]

Item	Unit	Angra 1	Angra 2	Angra 3
Net capacity	MW(e)	626	1275	1245
Load factor	%	83.7	90.4	90.4
Thermal efficiency	-	0.342	0.358	0.358
Discharge burnup	GWd/t HM	33	33	33
Residence time	days	1168	1168	1168
Construction time	years	10	19	16
Lifetime	years	60	40	40
Conversion	US$/kgU	6.75	6.75	6.75
Enrichment	US$/kg SWU	60	60	60
Fuel fabrication (UOX)	US$/kg HM	275	275	275
Cooling storage	US$/kg HM/ano	5	5	5
Natural uranium	US$/kg	40	40	40

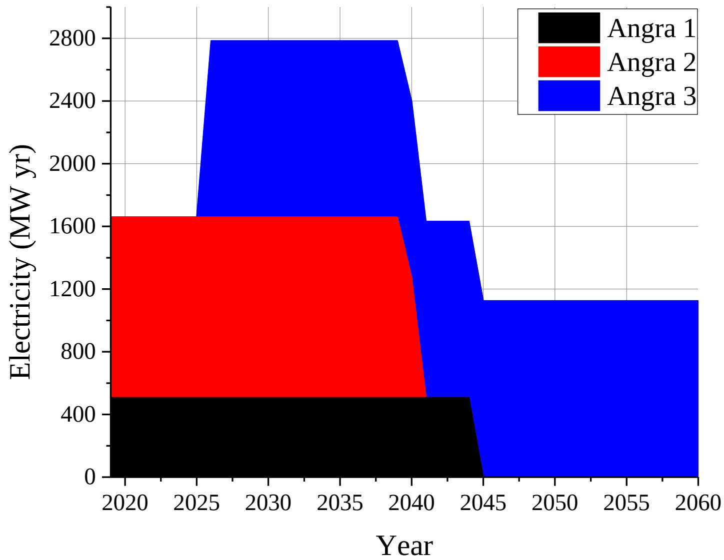
The second fuel is reprocessed using the UREX+ technique. The UREX+ reprocessing technique involves the recovery of a matrix composed of uranium (U), plutonium (Pu), neptunium (Np), americium (Am) and curium (Cm). The recovered isotopes are used in the manufacture of transuranic fuel later spiked in depleted uranium. The composition of transuranic fuel spiked in depleted uranium (TRU-U)O_2, is 8.9% TRU and 91.1% U on a heavy metal base, totaling 12.5% by weight of fissile material[17].

For both reprocessed fuels, their compositions guarantee an infinite multiplication factor close to the MOX fuel benchmark as can be seen in [17]. The reprocessing and manufacturing costs of transuranic fuels are defined as US$600/kg HM and US$1200/kg HM, respectively [6].

3. RESULTS AND DISCUSSION

The electricity supply from the Brazilian nuclear energy system, used as a basis for comparing the uses of different fuels, is shown in Figure 1. An increase in the total supply can be observed in 2026, due to the entry of Angra 3 into the nuclear system. A decrease is also noticeable in the 2040s when Angra 1 and Angra 2 will be deactivated and the total supply will become equivalent to the supply of Angra 3.

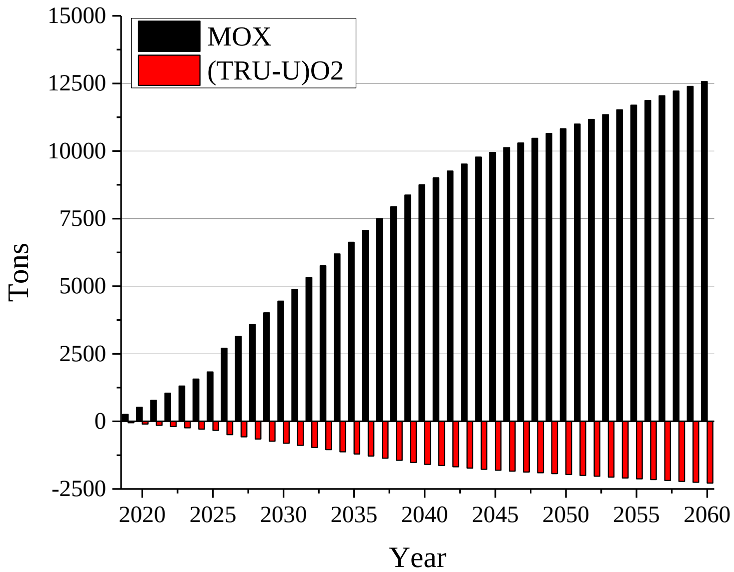
Figure 1: *Electricity Supply.*



Regarding the consumption of natural resources, natural uranium is used in the MOX fuel cycle. The accumulated consumption of the resource at the end of the period is around 15 thousand tons. On the other hand, the fuel cycle $(TRU\text{-}U)O_2$ does not use natural resources, since only depleted uranium is used to fabricate the fuel.

In Figure 2 the amounts of depleted uranium produced or consumed in each of the fuel cycles are shown. Although MOX fuel uses depleted uranium in its manufacture, it produces more than it consumes. Therefore, there is an increase in the depleted uranium inventory, reaching 12.5 thousand tons at the end of 2060. On the other hand, (TRU-U)O_2 consumes depleted uranium leading to a reduction in inventory. There is a reduction of around 2.3 thousand tons of the by-product.

Figure 2: *Depleted uranium inventories*.



Due to reprocessing in both fuel cycles, there is spent fuel consumption. This consumption is shown in Figure 3. MOX fuel consumes a relatively greater amount of spent fuel than (TRU-U)O_2 fuel. By the end of the period, MOX fuel consumes around 6060 tons of spent fuel, while (TRU-U)O_2 consumes around 230 tons.

The amounts of HLW produced by the fuel cycles are shown in Figure 4. The sum of spent fuel and reprocessing waste was considered. MOX generates greater amounts of HLW since it has greater reprocessing requirements than (TRU-U)O_2. About 8,600 tons of HLW are produced by MOX, while 2,600 tons are produced by (TRU-U)O_2.

Figure 3: *Spent fuel cumulative consumption*.

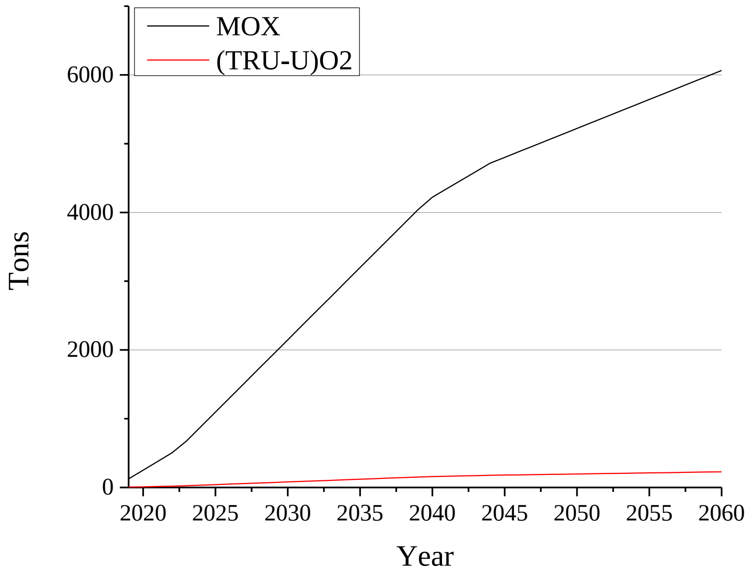
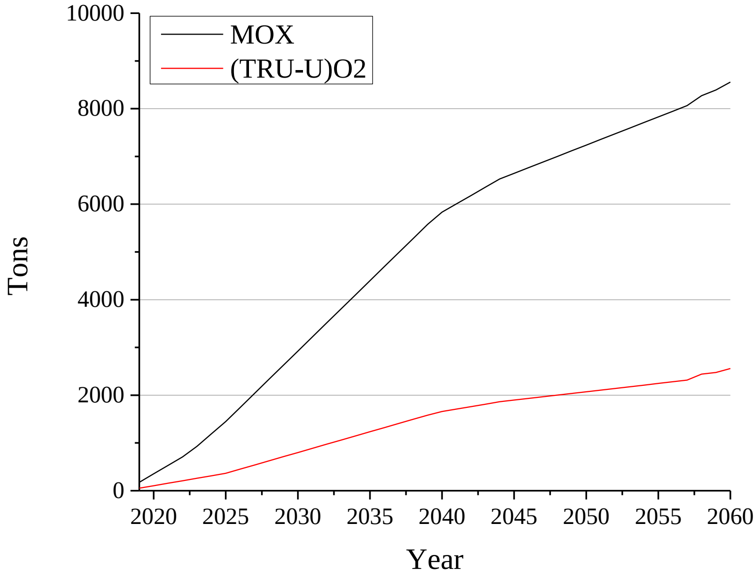


Figure 4: *Cumulative HLW generated*.



The economic data related to the fuel cycle costs for each scenario are presented in Figure 5 and Figure 6. Total annual expenses in the fuel cycle are composed by the sum of each stage of the nuclear fuel cycle. The peaks, in 2026, represent the beginning of the operation of Angra 3, where a larger amount of fuel is needed to carry out the first load of the nuclear power plant. Costs for each fuel cycle vary significantly. On the one hand, MOX has higher expenses for reprocessing, fuel fabrication and storage. Furthermore, MOX has natural uranium, conversion and enrichment costs (Figure 5). On the other hand, most of the (TRU-U)O_2 expenses come from fuel fabrication and do not have costs of natural uranium, conversion or enrichment (Figure 6). The differences in reprocessing costs can be explained by the different matrices used to fabricate the new fuel for each of the cycles. In the case of MOX, where only the plutonium matrix is used, the amount of spent fuel to be reprocessed, to fabricate the new fuel, is very large related to (TRU-U)O_2 (which uses a matrix containing reprocessed U, Pu, Np, Am and Cu), as can be seen in Figure 3. Therefore, the costs of reprocessing are higher in MOX. Another important fact to note is that, over time, the cost of storage will more effectively influence the total annual expenses in the fuel cycle. This occurs because, in the model, HLW remains in storage and has an annual cost of US$ 5/kg HM.

Figure 6: *Annual costs on MOX nuclear fuel cycle*.

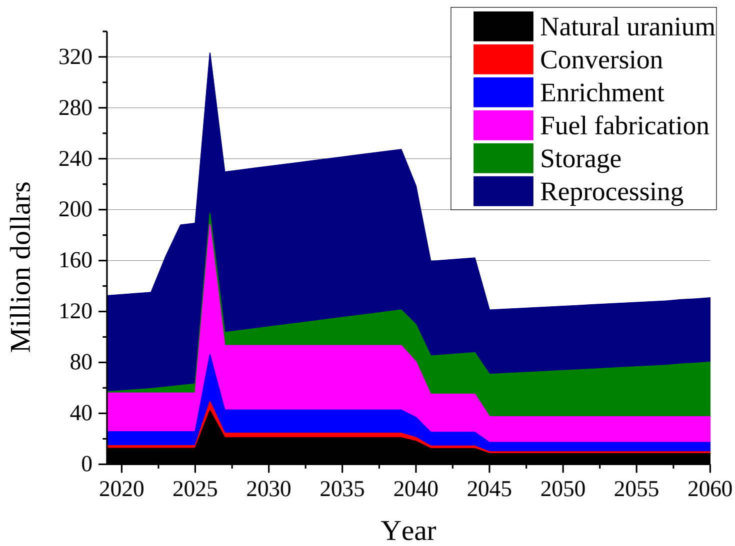
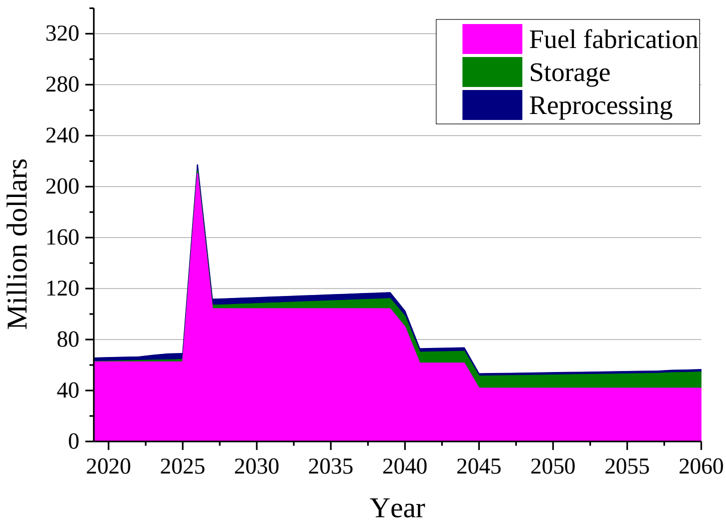


Figure 7: *Annual costs on (TRU-U)O_2 nuclear fuel cycle.*



Finally, in Table 2 the levelized unit fuel cost (LUFC) is presented for the period from 2019 to 2060, that is, it is the unit fuel cost to produce one unit of energy [18]. Therefore, this result allows comparing the unit costs of different fuel cycles to generate the same amount of energy. (TRU-U)O_2 is the cheapest fuel cycle, with a LUFC of US$ 5.06/MWh. The MOX fuel cycle is about twice as expensive as (TRU-U)O_2, with a LUFC of US$ 10.85/MWh.

Table 2: LUFC from 2019 to 2060.

Fuel	**MOX**	**(TRU-U)O_2**
LUFC (US$/MWh)	10.85	5.06

4. CONCLUSION

The present work has compared the two reprocessed fuel cycles. (TRU-U)O_2 proved to be more advantageous over MOX in almost all compared results. It does not require the extraction of new natural resources, consumes depleted uranium inventories, generates lower amounts of HLW and has nearly half the LUFC compared to MOX. The advantage presented by MOX compared to $(TRU-U)O_2$ was the use of larger amounts of spent fuel stored. This property may be necessary if the objective is the transmutation of the spent fuel. Future works intend to compare these fuels with conventional fuels and reprocessed fuels by other techniques to elucidate and direct studies towards more viable fuels.

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