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Long Term Comparison between Reprocessed Nuclear Fuel Cycles

Fidéllis B. G. L. e Estanislau[1], Carlos E. Velasquez[2], Antonella L. Costa[3], and Claubia Pereira[4]

[1]fidellis01@gmail.com,[2]carlosvelcab@nuclear.ufmg.br,[3]antonella@nuclear.ufmg.br,[4]claubia@nuclear.ufmg.br
Universidade Federal de Minas Gerais - Departamento de Engenharia Nuclear
Av. Antônio Carlos, 6627, Campus Pampulha, 31270-901, Belo Horizonte, MG, Brasil

1. Introduction

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: a) a closed fuel cycle with recovering of plutonium (Pu) to fabricate the mixed oxide (MOX) fuel; b) 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.

2. Methodology

The comparison of the fuel cycles is done through modeling using the MESSAGE software. The model allows projecting the use of resources, material and tailings flows, import dependencies, investment needs and other costs for energy supply, which makes it a convenient choice for the study carried out [1].

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 [2]. 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) [3] and starts operating in 2026 [4]. The nuclear reactors at the three plants are PWR and the reactors from Angra 2 and Angra 3 are identical [5]. The technical data considered in this work, referring to each of the three plants, can be found in Table I.

Table I: Technical and economic characteristics [1, 3, 5, 6, 7, 8, 9]

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 fuel cycles consider the reprocessing of an usual uranium oxide (UOX) from a PWR with initial enrichment of 3,1% and burnup of 33 GWd/t HM [10]. The mixed oxide (MOX) fuel is fabricated from 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 [11]. Nuclear power plants utilizes one-third of MOX and two-thirds of UOX fuel in their core.

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 $(TRU\text{-}U)O_2$, is 8.9% TRU and 91.1% U on a heavy metal base, totaling 12.5% by weight of fissile material[12].

For both reprocessed fuels, their compositions guarantee an infinite multiplication factor close to the MOX fuel benchmark as can be seen in [12]. The reprocessing and manufacturing costs of transuranic fuels are defined as US$600/kg HM and US$1200/kg HM, respectively [1].

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 Fig. 1.

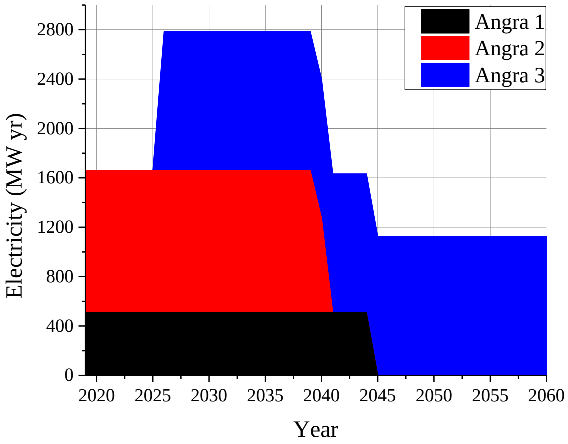

Figure 1: Electricity supply.

The cumulative consumption of natural resources for MOX and $(TRU\text{-}U)O_2$ fuels is shown in Fig. 2a. 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. The fuel cycle $(TRU\text{-}U)O_2$ does not use natural resources, since only depleted uranium is used to manufacture the fuel.

In Fig. 2b 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, $(TRU\text{-}U)O_2$ consumes depleted uranium leading to a reduction in inventory. There is a reduction of around 2.3 thousand tons of the by-product.

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

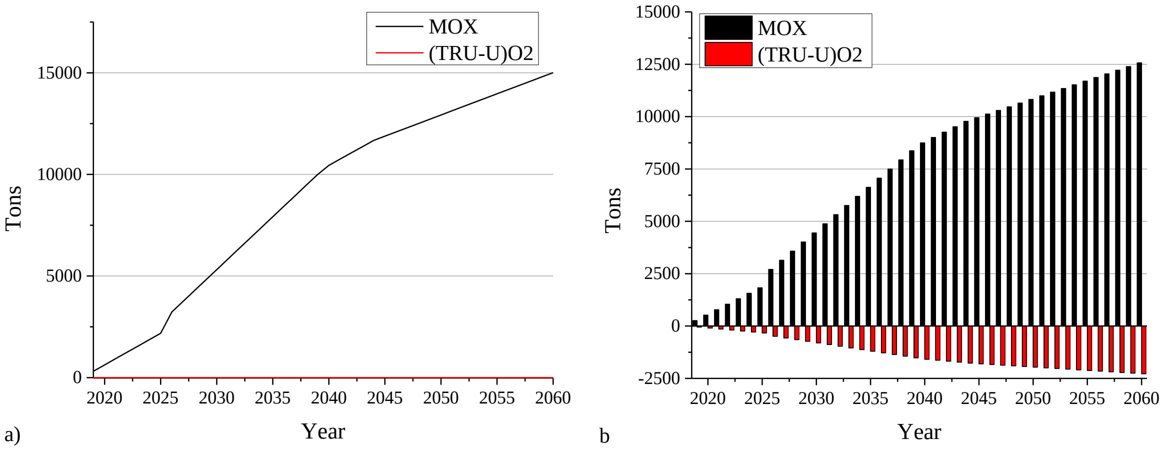

Figure 2: a) Cumulative consumption of natural resources; b) Depleted uranium inventories.

The amounts of HLW produced by the fuel cycles are shown in Fig. 3b. 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.

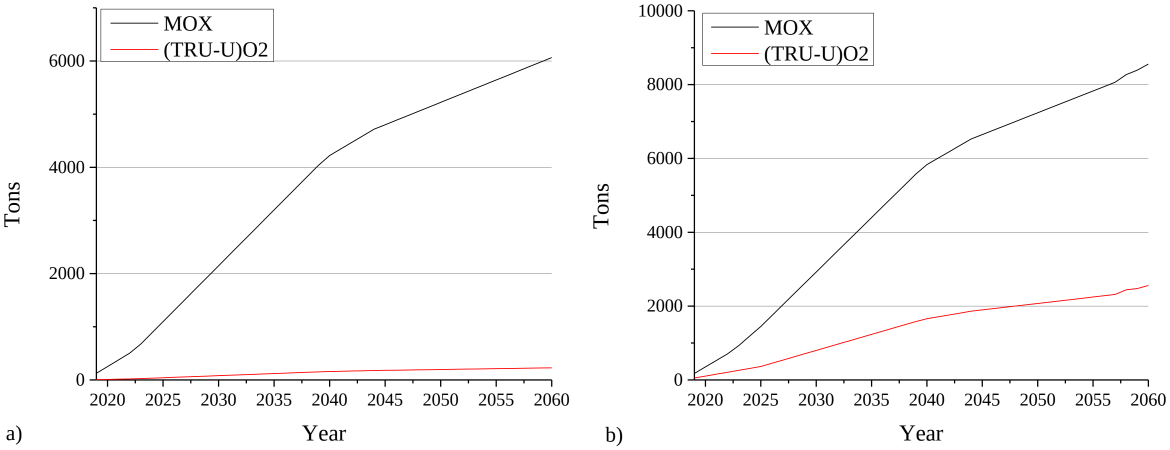

Figure 3: a) Spent fuel cumulative consumption; b) Cumulative HLW generated.

Finally, in Table II 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 [13]. 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 \$5.06/MWh. The MOX fuel cycle is about twice as expensive as (TRU-U)O_2, with a LUFC of \$10.85/MWh.

Table II: LUFC from 2019 to 2060

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

4. Conclusions

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 $(TRU\text{-}U)O_2$ 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 by other techniques in order to elucidate and direct studies towards more viable fuels.

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