PHYSOR 2004 – The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

Studies of a Deep Burn Fuel Cycle for the Incineration of Military Plutonium in the GT-MHR using the Monte-Carlo Burnup Code

Alberto Talamo* and Waclaw Gudowski
Department of Nuclear and Reactor Physics
Royal Institute of Technology, 10044 Stockholm, Sweden

Abstract

The graphite moderated and helium cooled reactors may play an important role in the future development of nuclear energy because of their unbeatable benefits: passive safety mechanism, low cost, flexibility in the choice of fuel, high conversion energy efficiency, high burnup, more resistant fuel cladding (because of the TRISO particles) and low power density. General Atomic possesses a long time experience with this type of reactors and it has recently developed a design in which this type of reactor is structured into 4 modules of 600 MW_{th}: the Gas Turbine – Modular Helium Reactor (GT-MHR). Since the GT-MHR offers a rather large flexibility in the choice of fuel type, Th, U, and Pu may be used in the manufacture of fuel with a quite ample degree of freedom. As a consequence, the GT-MHR may operate for very different purposes: e.g. the reduction of waste production trough fuel cycles based on thorium, which is quite attractive proposal for countries which approach for the first time the market of nuclear energy, the transmutation of LWRs waste or military Pu.

In the previous studies we analyzed the behavior of the GT-MHR with a fuel built on LWRs waste; whereas, in the present studies we tried to focus on the incineration of military Pu. This choice of fuel requires a detailed numerical modeling of the reactor, since the pretty high value of k_{eff} at the beginning of the fuel cycle does not allow to neglect the control rods and burnable poison in the computing simulations. By contrast, when the reactor is fueled with LWRs waste the breeding of fissile isotopes, at the equilibrium of the fuel composition, keeps almost constant and close to the criticality the value of k_{eff}.

Keywords: GT-MHR, TRISO, military plutonium, MCNP, MCB, Deep Burn

* Corresponding author, Tel. +46-8-55378204, E-mail: alby@neutron.kth.se

1. Introduction

In our previous [1-2] studies we demonstrated the capacity of the Gas Turbine Modular - Helium Reactor (GT-MHR) [3] to operate on a fuel cycle based on Light Water Reactors (LWRs) waste. It has been found that this reactor reaches the equilibrium of the fuel composition after 12 years of operation and the reduction of ^{239}Pu, Pu and all actinides reaches 94%, 61% and 53%, respectively. This good performance is a result of the *Deep Burn* fuel cycle strategy. This strategy is based on use of two types of fuels: a Driver Fuel (DF) and a Transmutation Fuel (TF). DF is maintaining the criticality of the reactor by the fission of fissile isotopes. TF "controls" reactivity of the reactor by the neutron capture of non-fissile actinide isotopes followed by fission or natural decay. In this scenario, the negative reactivity feedback offered by the TF allows the reactor to operate without burnable poisons. The outstanding capacity of TRISO particles to allow an irradiation time of over three years, because of a burnup limit of 700000 MWd, enables a fuel management strategy with 3-year fuel residency time. Initially, the reactor is loaded with the DF consisting of $NpPuO_{1.7}$, in an isotopic composition coming from the reprocessed LWRs waste. Then the TF consisting of irradiated DF plus some set-aside $AmCmO_{1.7}$, coming from the separation of the LWRs waste is loaded into the core. After 6 years of operation, the GT-MH Reactor is close to equilibrium and the reactivity margin is small enough [1, fig. 8] to neglect modeling of control rods in the numerical simulations.

2. Adapting the Deep Burn strategy to a military plutonium fuel cycle

In the present studies we tried to adopt the *Deep Burn* strategy to a fuel cycle based on military plutonium with 96% of ^{239}Pu. In this case, the irradiated DF is so rich in fissile isotopes that the TF cannot guarantee a negative reactivity feedback, and the presence of erbium as burnable poison is absolutely necessary for the reactivity safety reasons. At beginning of life (BoL) the fuel is composed of DF, consisting of fresh military plutonium; after an irradiation period of three years the fuel is reprocessed into Post Driver Fuel (PDF), with isotopic composition of the spent DF. To be compatible with our previous papers and with an established convention, we refer herewith to the TF as PDF and we assume that PDF actinide isotopic composition corresponds to the three year irradiated DF. However, the reactor requires the presence of erbium as burnable poison because the PDF is still a very "reactive" fuel due to the high residual ^{239}Pu content. Moreover, to ensure a proper reactivity management in this reactor core we introduced in the numerical calculations modeling of control rods.

3. The Gas Turbine – Modular Helium Reactor concept

In the GT-MHR, the fuel is disposed into 3 concentric rings of hexagonal blocks. The reactor is equipped with 12 startup control rods, 18 shutdown ones and 36 operational ones; we modeled all of them, but we used only the operational in the approach to the equilibrium of the fuel composition (fig. 1).

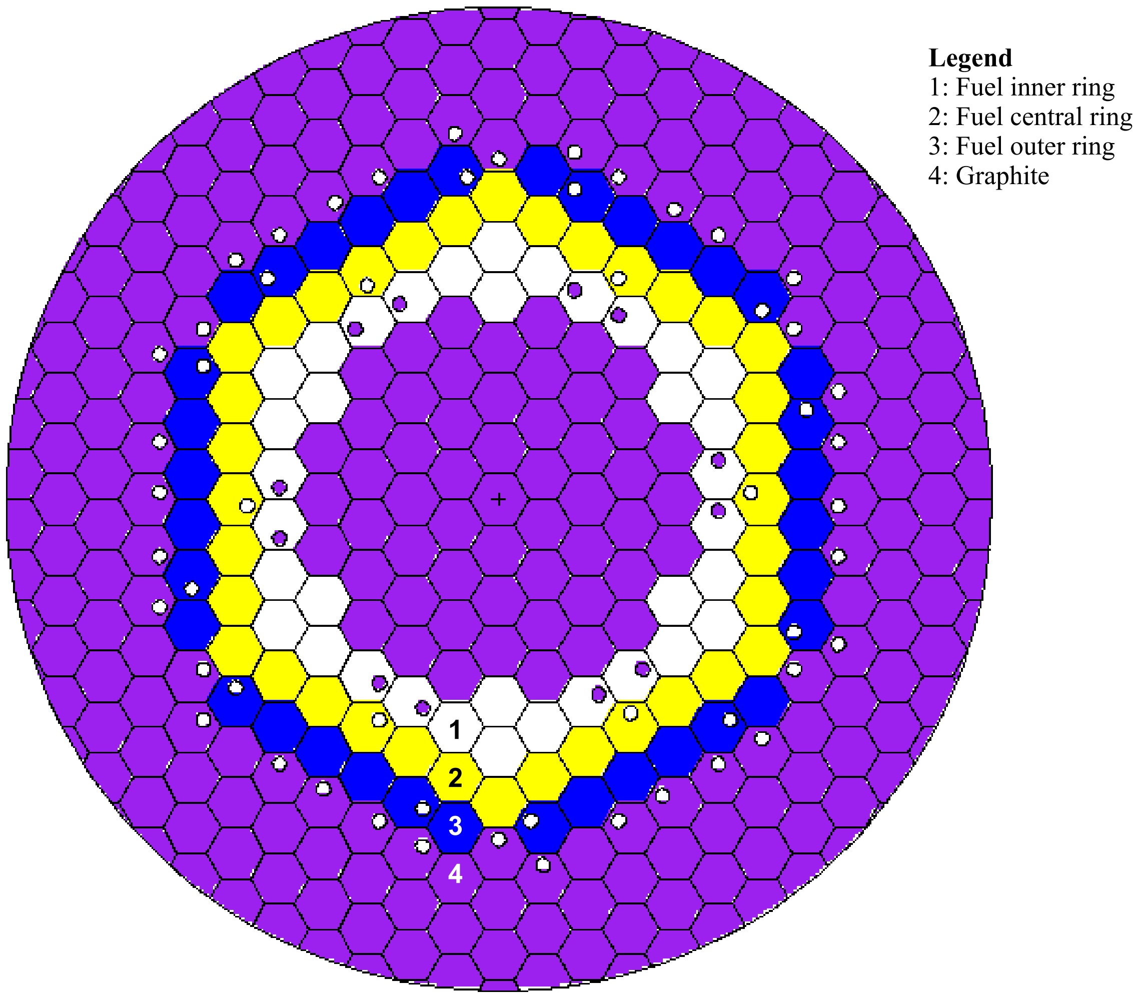

Figure 1: *GT-MHR core design. The inner ring of fuel (white) contains 12 startup control rods, the central (yellow) and outer ring (blue) respectively do 6 and 12 shutdown control rods, the outer graphite reflector ring does 36 operational control rods.*

Each control rod consists of a graphite matrix filled by TRISO particles of boron carbide. The burnable poison consists of 6 rods per hexagonal fuel block of erbium TRISO particles dispersed in a graphite matrix (fig 2). Each hexagonal fuel block of the GT-MHR contains 144 DF and 72 PDF pins in the case it is not equipped with control rods, otherwise it does 124 DF and 64 PDF pins.

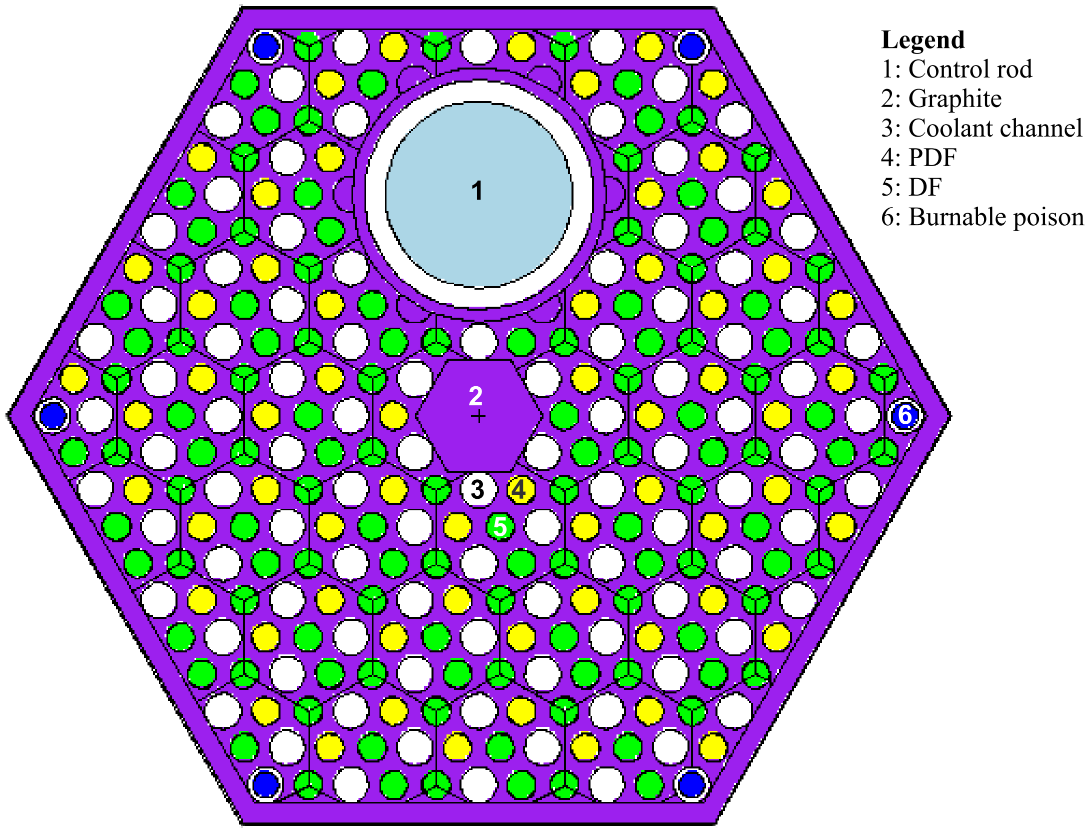

Figure 2: *Hexagonal fuel block. The graphite matrix contains 95 coolant channels (white), 124 DF pins (green), 62 DF pins (yellow), 6 burnable poison pins (blue) and 1 (startup/shutdown) control rod (light blue).*

The GT-MHR has been modeled with the MCNP/MCB codes [4-5] based on an original design of General Atomic (GA) [3]. Some important core parameters have been altered in order to optimize reactor performance. The radius and packing ratio of TRISO kernels for DF and PDF have been set equal, since we observed that this parameter does not affect significantly the averaged capture-to-fission ratio of fuel [2]. Moreover, we substituted the silicon carbide of TRISO particles with zirconium carbide (ZrC), since ZrC coated fuel resists higher temperatures in the case of accidental conditions. Finally, we replaced boron with erbium as burnable poison.

The geometry and material data of the GT-MHR are respectively shown in table 1 and 2.

Table 1: *Geometry data of the GT-MHR.*

Core – radius [cm]	350
Core – height [cm]	1000
Control rods – startup (inner ring)	12
Control rods – operational (outer moderator reflector ring)	36
Control rods – shutdown (central ring/outer ring)	6/12
Control rods – internal radius (startup/operational/shutdown) [cm]	0/2.64/0
Control rods – external radius [cm]	4.13
Control rods – hole radius [cm]	5.05
Control rods – distance from the center of the hexagon [cm]	9.75614
Control rods – height at BoL (startup/operational/shutdown) [cm]	0/647/0
Hexagonal fuel blocks – number	36x3
Hexagonal fuel blocks – side [cm]	17.99844
Hexagonal fuel blocks – height [cm]	793
Hexagonal blocks – interstitial gap [cm]	0.1
Fuel blocks – DF pins (with control rod/without control rod)	140/124
Fuel blocks – PDF pins (with control rod/without control rod)	70/62
Fuel blocks – burnable poison pins	6
Fuel blocks – coolant channels (with control rod/without control rod)	108/95
Pins – radius (fuel/burnable poison) [cm]	0.6223/0.5715
Pins – distance between pins [cm]	3.25628
Pins – hole radius (fuel/coolant channel/burnable poison) [cm]	0.635/0.795/0.795
Pins – height [cm]	793
TRISO particles – kernel radius (DF/burnable poison) [cm]	0.015/0.035
TRISO particles – width porous carbon layer (DF/burnable poison) [cm]	0.015/0.0025
TRISO particles – width inner pyrocarbon layer (DF/ burnable poison) [cm]	0.0035/0.0035
TRISO particles – width ZrC layer (DF) [cm]	0.0035
TRISO particles – width outer pyrocarbon layer (DF) [cm]	0.0040
TRISO particles – distance between particles [cm]	0.0794138

Table 2: *Material data of the GT-MHR.*

Material	***Atomic percentage***	***Density at BoL [g/cm³]***
TRISO $PuO_{1.7}$	^{239}Pu (34.83%) ; ^{240}Pu (2.21%) ; ^{16}O (62.96%)	10.2
TRISO porous graphite	C (100%)	1
TRISO pyrocarbon	C (100%)	1.85
TRISO ZrC	Zr (50%) ; C (50%)	6.56
Graphite	C (100%)	1.74
Control rods (B_4C)	^{10}B (72%) ; ^{11}B (8%) ; ^{16}O (20%)	2.47
Burnable poison (Er_2O_3)	^{166}Er (23.77%) ; ^{167}Er (16.23%) ; ^{16}O (60%)	4.89

4. The approach to equilibrium

The fuel cycle adopted for this reactor concept has a residency time of 3 years, with a refueling and shuffling period of one year. At BoL and after each refueling of the reactor, the central ring is loaded with fresh DF. At the beginning of the 2nd year, the one-year irradiated DF is moved from the central ring into the inner one. At the beginning of the 3rd year, the one year irradiated fuel of the central ring is shuffled into the outer ring and this operation repeats in the following years; the inner ring retains its DF. At the beginning of the 4th year, the 3 year irradiated DF of the inner ring becomes PDF and fills the central ring together with fresh DF; the two years irradiated DF from the outer ring moves into the inner one and this operation repeats in the following years. At the beginning of the 5th year the inner ring is filled with PDF from its 3 year irradiated DF; the central ring retains its PDF. At the beginning of the 6th year, the inner ring keeps its PDF; the central ring also keeps its PDF; the outer ring loads with the PDF from the three years irradiated DF of the inner ring. In the following years the reactor operates with the same configuration of the 6th year; therefore, after the 6th year the shuffling policy assumes the following permutations:

- DF inner ring ⇒ DF outer ring.
- DF central ring ⇒ Fresh fuel
- DF outer ring ⇒ DF central ring
- PDF inner ring ⇒ PDF outer ring
- PDF central ring ⇒ PDF inner ring
- PDF outer ring ⇒ DF inner ring

The detailed description of the refueling and shuffling strategy during the first 6 years is shown in fig. 3.

Concerning the management of control materials, we applied a residency time of 6 years for the control rods and 1 year for the burnable poison.

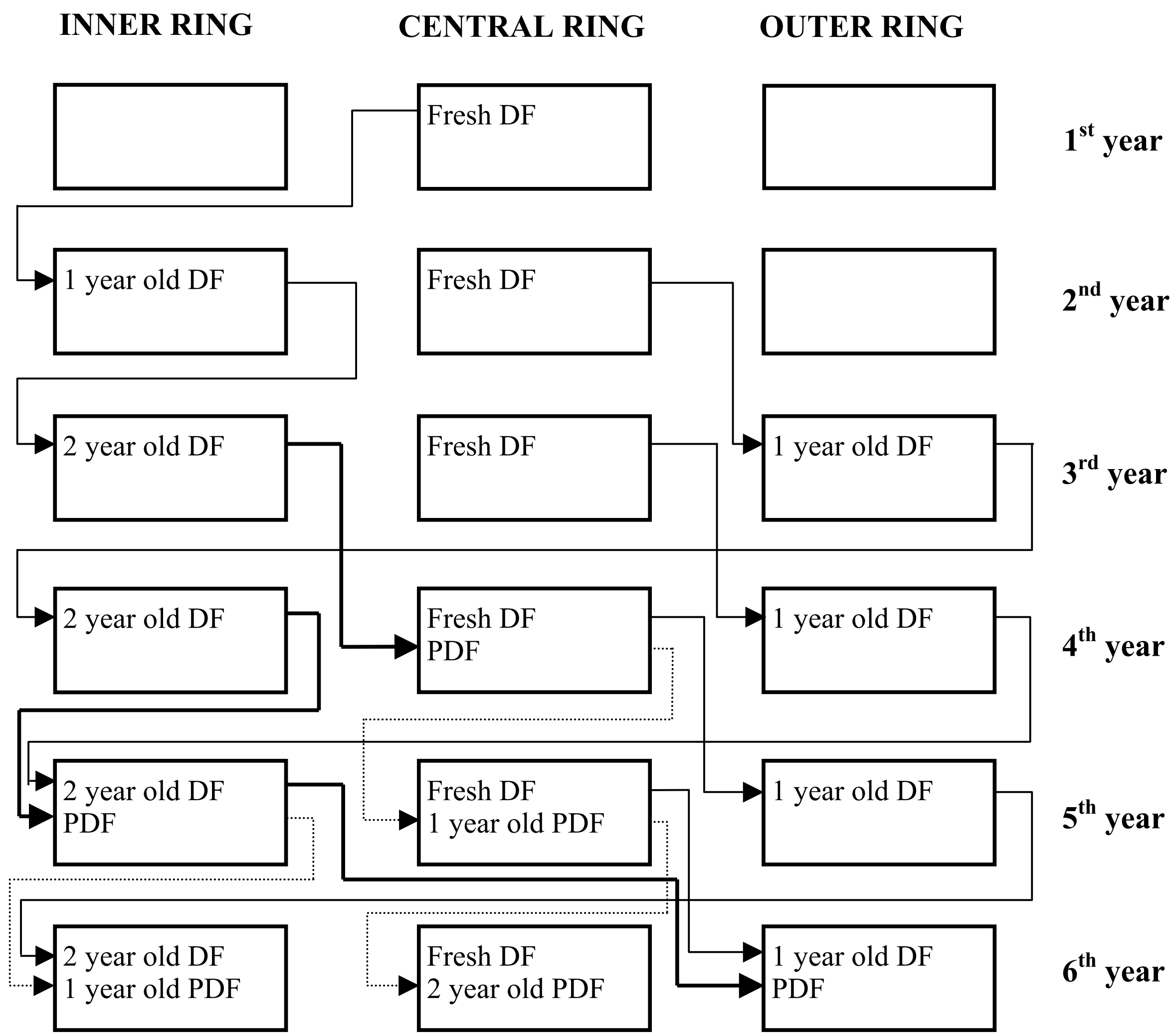

Figure 3: *Refueling and shuffling schedule during the first 6 years.*

5. The incineration of military plutonium

Fig. 4 shows the values of k_{eff} starting from the BoL up to the equilibrium 12th year. Blue color indicates the beginning of each year, read color does its corresponding end. During the first 2 years not all 3 rings are loaded with fuel, therefore the total amount of burnable poison is lower and consequently k_{eff} of "reactive" load is higher. The initial k_{eff} value at the first year is lower than that one at the second because fuel is loaded only in one ring. At third year, k_{eff} drops down as a combined effect of burnup and burnable poison content. Since the third year of operation, the k_{eff} values smoothly increases to the asymptotic value as a result of the fuel management strategy. The subcritical value of k_{eff} at the end of the 3rd year can be easily adjusted by the withdrawn of the operational control rods, which cover only 647 cm of the available 793 cm.

During all simulation steps control rods were kept at the constant position in the reactor (see table 1) core leaving the sufficient margins for reactivity compensations, particularly at 3rd year of operation.

After an irradiation of three years, the GT-MHR transmutes about 66% of the ^{239}Pu mass of the DF (fig. 5); at the same time, the fraction of ^{240}Pu accumulates and a small quantity of ^{241}Pu builds up; whereas, the production of ^{242}Pu and ^{241}Am remains limited to a few kilograms.

Since 50% of the mass of the irradiated DF becomes PDF the right columns of fig. 6 are equal to the left ones of fig. 5 divided by 2. In the irradiation of PDF the concentration of ^{239}Pu and ^{240}Pu respectively diminishes 75% and 53%. Among the isotopes of the spent PDF, ^{238}Pu and ^{241}Pu decay within few hundreds of years and therefore they do not pose any risk for the safety of the geological repository. In addition, the residual quantities of Am and Cm isotopes are so small that they do not arise particular problems in the managing of the spent PDF comparing to that one of LWRs waste; also ^{242}Pu production is quite moderated (about 5 kg).

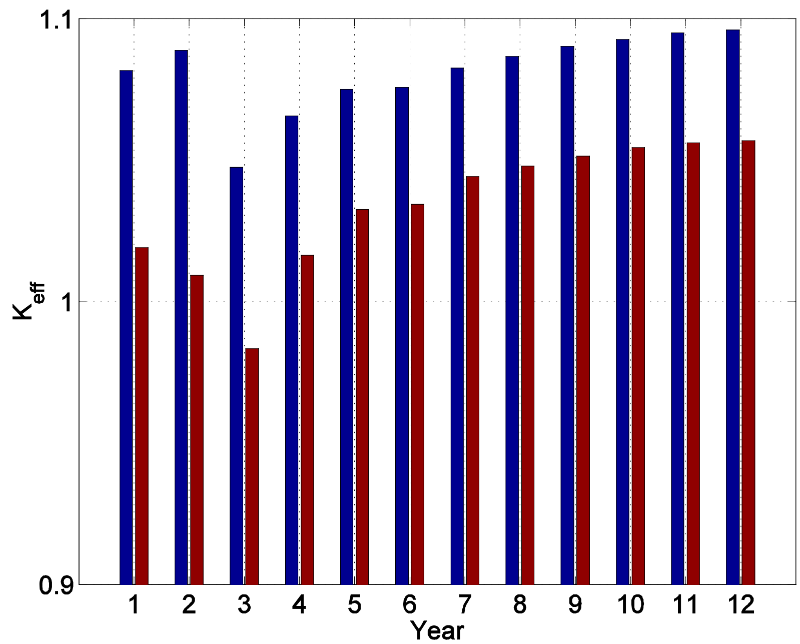

Figure 4: *Evolution of k_{eff} during the first 12 years. All values have a relative standard deviation lower than 0.06%.*

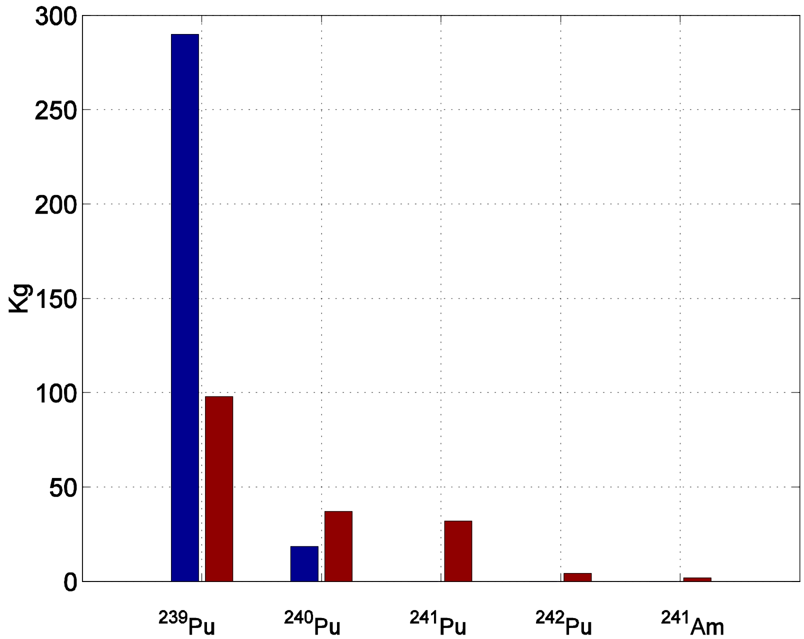

Figure 5: *Mass of the most abundant actinides of the fresh DF (central ring at beginning of the 12^th^ year) and after three years irradiation (inner ring at the end of the 12^th^ year).*

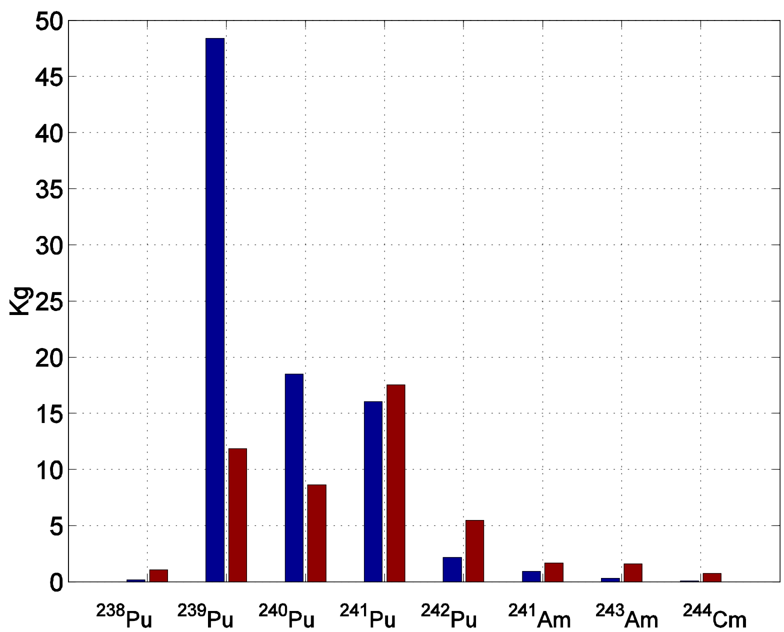

Figure 6: *Mass of the most abundant actinides of the fresh PDF (outer ring at beginning of the 12^th^ year) and after three years irradiation (central ring at the end of the 12^th^ year).*

6. Conclusions

The adapting of the Deep Burn strategy to a fuel cycle based on military plutonium forces to use erbium as burnable poison; in addition, the numerical simulations must include the modeling of control rods because of the high initial reactivity of the reactor.
The GT-MHR loaded with military plutonium has proved to satisfy the k_{eff} constraints during the approach to equilibrium.
The mass flow of the GT-MHR fueled by military plutonium at the equilibrium of the fuel composition shows that 66% of ^{239}Pu is burned in three years and 92% in six years. The radiotoxicity of the fission products equals the level of natural uranium after few hundreds of years leaving in the long run the ^{239}Pu as the major contributor to the radiotoxicity PDF waste. Nevertheless, the ^{239}Pu extraction from the spent PDF for military purposes poses some technological problems since it would be necessary to process over 10^{10} TRISO particles to reach the critical mass of ^{239}Pu. Finally, the spent PDF constitutes a safe form of waste because the TRISO particles have proven to keep intact for hundreds of thousands years, even if they would permanently be flooded with groundwater.

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